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MULTIPLE PRIMARY BRONCHOGENIC CARCINOMA

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In 1869 Theodor Billroth recorded the first case of multiple primary cancer.[5] Since that time a large number of reports of multiple primary malignancies in the same or different organs have been recorded. As the relation of multiple primary cancers in the same individual has become more evident, it is apparent that this association is more than fortuitous. Warren and Gates summarized this point of view in a review entitled "Multiple Primary Malignant Tumors" which dealt with multiple cancer in the same as well as in different organs: "An individual with one cancer is more apt to develop a second cancer than he would be expected to do by chance alone. This implies a definite predisposition or susceptibility to cancer in certain persons or exposure to some influence favoring the development of cancer."[47] In certain single or paired organs, the occurrence of multiple primary malignancies is becoming recognized with increasing frequency. This is particularly true in skin, oropharynx, stomach, colon, ovary, and breast.[13, 22, 30, 40, 41, 43, 44, 47] If "pulmonary adenomatosis" and "multiple alveolar cell" carcinomas (bronchiolar carcinomas) are excluded, the occurrence of multiple bronchogenic carcinomas has hardly been considered. To the best of our knowledge only 26 cases of definite multiple primary invasive bronchogenic carcinomas have been reported. These are listed in Table I. Three patients had a resection of the original primary lesion before the development of a second lung cancer. The latter cases are also listed in Table II. In Stewart's patient, a second primary lesion developed 6 years after lobectomy for the initial bronchogenic carcinoma. Until now Stewart's report presented the longest time interval between resection of the original lesion and development of the second primary carcinoma.[43] The following 2 case reports concern

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patients who were considered to have a second primary epidermoid carcinoma of the bronchus after resection of the original tumor—one 9 years and one 10 years after pneumonectomy for the first lung cancer.

TABLE I. MULTIPLE PRIMARY BRONCHOGENIC CARCINOMA

AUTHOR	NUMBER OF CASES	YEAR
1. Chauvet and Feuardent[11]	1	1954
2. Drash and DeNiord[16]	1	1958
3. Gurkan[18]	1	1958
4. Howard and Williams[23]	1	1957
5. Junghanns[24]	1	1929
6. Kainberger[25]	1	1955
7. Mandel and Thomas[26]	1	1959
8. McGrath, Gall, and Kessler[27]	5	1952
9. Muller[28]	1	1930
10. Newman and Adkins[29]	1	1958
11. Pirchan and Sikl[33]	1	1932
12. Robinson and Jackson[36]	9	1958
13. Stewart[43]	1	1957
14. Williams[49]	1	1952
15. Hughes and Blades	2	1960
	28	

TABLE II. DEVELOPMENT OF SECOND PRIMARY BRONCHOGENIC CARCINOMA AFTER RESECTION OF INITIAL LESION

AUTHOR	NO. CASES	YEARS BETWEEN RESECTION AND DISCOVERY	YEAR
1. Robinson and Jackson[36]	1	5	1958
2. Stewart[43]	1	6	1957
3. Williams[49]	1	3	1952
4. Hughes and Blades	2	9 and 10	1960

CASE REPORTS

CASE 1.—On June 2, 1948, a 43-year-old man was admitted to the Surgical Service of The George Washington University Hospital because of cough of 8 months' duration. Two months before hospital admission, a roentgenogram of the chest showed an opacity in the left lung field. Six weeks later, following a second film, the patient was referred to The George Washington University Hospital. Other than the cough, he related no abnormal symptoms. He had smoked a package and a half of cigarettes a day for most of his adult life. The patient stated that his mother had died with lung cancer. A prominent left hilar shadow and a round opacity peripheral to the left hilum could be seen on the admission chest roentgenogram (Fig. 1). At thoracotomy, a 7 by 4 by 5 cm. mass was found in the anterior portion of the left upper lobe. Since the lesion involved both lobes, a left pneumonectomy was performed. The tumor was a grade 3 epidermoid carcinoma. Seven hilar lymph nodes were negative for metastasis. The postoperative course was uncomplicated and he was discharged on the twelfth postoperative day.

Nine years after pneumonectomy a nodular opacity in the right lung field was present in a routine chest roentgenogram (Fig. 2). The patient was again admitted to The George Washington University Hospital. He was asymptomatic and on physical examination, the findings were those expected after a pneumonectomy. The maximum breathing capacity was 81.6 L. per minute and vital capacity was 2,177 c.c. Normal calculated maximal breathing capacity for him was estimated to be 110 to 144 L. per minute. The electrocardiogram was within normal limits. At thoracotomy, a 3.5 by 3 by 3 cm. mass was found in the superior segment. There was no evidence of mediastinal involvement. A superior segmental resection and prophylactic tracheostomy were performed. Pathologic diagnosis was grade 3 epidermoid

carcinoma. Carcinoma in situ was noted in the bronchial mucosa. The patient's postoperative course was uneventful. During the last few days in the hospital he was given a course of intravenous oxapentaethylene phosphoramide (MEPA). He was discharged on the ninth postoperative day.

Two and one-half months after the segmental resection, a 1 by 2 cm. density was noted in the chest roentgenogram. Five months postoperatively he experienced weakness of the left leg and 2 weeks later he had a Jacksonian seizure in the left upper and lower extremities.

Six months after the second pulmonary resection the patient was admitted to The George Washington University Hospital for the third time because of a left hemiparesis and repeated left-sided Jacksonian seizures. The right hilar density had increased remarkably on the roentgenogram. A right carotid arteriogram demonstrated a probable metastasis in the right parietal region. Anticonvulsant medication as well as a second course of intravenous chemotherapy was given. Following discharge, he did poorly. Terminal care was carried out at another hospital. No autopsy was performed.

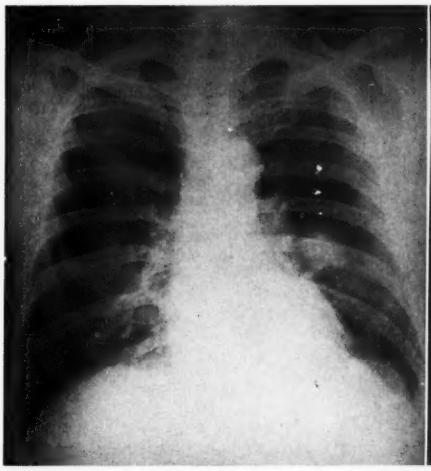

Fig. 2.

Fig. 1.

Fig. 1.—Case 1. A roentgenogram of a 43-year-old man. A left hilar opacity is present. Left pneumonectomy was performed for a grade 3 epidermoid carcinoma of the left lung.

Fig. 2.—Case 1. A roentgenogram made 9 years after pneumonectomy for epidermoid carcinoma of the left lung. A right hilar mass is now present. A right superior segmental resection was performed for the removal of grade 3 epidermoid carcinoma of the right superior segment. There was no evidence of involvement of the mediastinum.

CASE 2.—A 55-year-old man was admitted to the Surgical Service of The George Washington University Hospital on June 16, 1949, because of cough and left chest pain of 6 months' duration. A roentgenogram had been taken at the onset of his symptoms and he was told to return in 6 months for a follow-up film. During the next 3 months his symptoms persisted. He became increasingly fatigued and anorexic. A bronchoscopy was performed at another institution 3 months after the onset of the symptoms. During the ensuing 3 months he did poorly. His lack of appetite persisted and he lost 13 pounds in weight. Ten days before admission to The George Washington University Hospital he had coughed up bright red blood-streaked sputum and had noted wheezing in the chest. He had smoked a package of cigarettes a day for most of his adult life.

On examination, positive findings were confined to the left chest where dullness, friction rub, bronchial breathing, and an expiratory wheeze were noted. The radiologist's interpretation of the admission roentgenogram was atelectasis of the lingula, emphysema of the left basilar segments, probably due to bronchogenic carcinoma.

At bronchoscopy the left upper lobe bronchus was partially occluded by a mass which was in such a position that biopsy could not be taken. At thoracotomy a 2.5 by 1.5 by 1 cm. mass was palpated in the hilum of the left lung. A left pneumonectomy was performed. The pathologic diagnosis was grade 2 epidermoid carcinoma. Carcinoma in situ was noted in the adjacent bronchial mucosa. The postoperative course was uneventful and he was discharged on the eighth postoperative day.

During the first 5 years after pneumonectomy, roentgenograms were not remarkable. After 10 years he experienced increased cough, productive of bloody sputum. He was again admitted to The George Washington University Hospital. Diffuse inspiratory wheezes were present over the right lung field. On the oblique chest roentgenogram, there was a right hilar density (Figs. 3 and 4). At bronchoscopy, a tumor which protruded from the right upper lobe bronchus was biopsied. The pathologist's report was epidermoid carcinoma of the right upper lobe bronchus. A course of intravenous nitrogen mustard was administered. He was then treated with radiation and at present is doing satisfactorily.

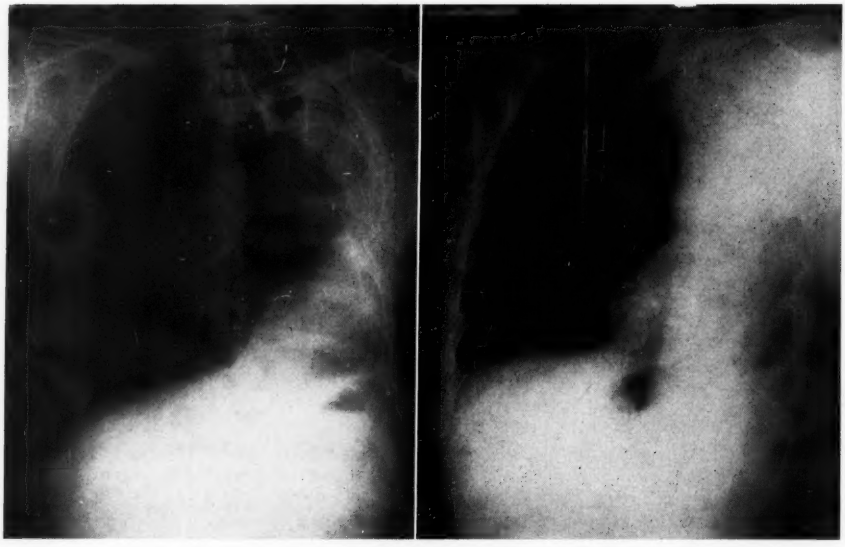

Fig. 3. Fig. 4.

Fig. 3.—Case 2. A roentgenogram of a 55-year-old man made 10 years after left pneumonectomy for grade 2 epidermoid carcinoma of the left lung. Current symptoms were cough and hemoptysis. A mass is present behind the thoracic spine which is difficult to see on the roentgenogram. Bronchoscopy established the presence of a new primary epidermoid carcinoma of the right upper lobe bronchus. There was no evidence of tumor in the left bronchial stump.

Fig. 4.—Case 2. A second primary epidermoid carcinoma of the right upper lobe can be seen on the oblique roentgenogram of the chest.

DISCUSSION

In each case it appeared that the initial lesion was completely removed. There was no metastatic hilar lymph node involvement. The fact that in one patient lung cancer developed in a contralateral bronchus 9 years after and in the other patient 10 years after the initial resection is not unequivocal proof that the second lesions represented new primary bronchogenic carcinomas. However, in both cases the pathologist found evidence of direct invasion from the bronchial mucosa in each new primary lesion. This histologic finding is strong

evidence that the second lesion in each case represented a new primary bronchogenic carcinoma. On the basis of the time interval after the original operation, gross morphology, and histologic description, it would seem that the second neoplasm in each case represents the growth of a new primary bronchogenic carcinoma.

The incidence of multiple primary lung cancer is probably far higher than that recorded in the literature. There are several good reasons that the occurrence of multiple bronchogenic carcinoma has not been recognized more frequently:

1. At postmortem examination, terminal lung cancer may be so widespread that differentiation between a new primary and an extension or metastasis of the original lesion is not appreciated or sought for.

2. The published cases of multiple primary cancers of the bronchus have been most frequently of the epidermoid type. If both tumors are epidermoid carcinomas, the relationship of overlying mucosa to underlying lymphatics and parenchyma is the most important factor in distinguishing between a new primary lesion and a spread of the initial lesion. If only lymphatics or parenchyma are involved, without evidence of invasive carcinoma in overlying mucosa, the lesion is probably metastatic. Invasive carcinoma arising from bronchial mucosa, distant to another frank bronchial cancer, is evidence that the second lesion is primary. A search for this relationship is not always carried out.

3. Tissue from surgical or autopsy specimens is most often cut from gross tumor and suspicious-looking lymph nodes. Small pre-invasive or invasive bronchogenic carcinomas are not usually searched for. Heretofore, routine sections of the bronchi have not been a part of autopsy protocol.

4. The course of lung cancer is often so rapid that death ensues before a second primary lesion becomes manifest. Moreover, the low 3-year survival of patients operated upon leaves a small number of these patients sufficient time to develop a second carcinoma.

5. Finally, the development of multiple bronchogenic carcinomas is not usually suspected.

MULTICENTRIC ORIGIN OF BRONCHOGENIC CARCINOMA

More and more evidence is accumulating in support of the multicentric origin of bronchogenic carcinoma. Many students of the disease are finding a high incidence of premalignant change throughout the bronchial tree in patients with known invasive bronchial carcinoma.[4, 6, 19, 20, 27, 37, 38, 42, 43, 46, 49] Basal cell hyperplasia, stratification, squamous metaplasia, and carcinoma in situ are cited as premalignant bronchial changes, although there is not complete agreement about the first three types of change and their relation to invasive cancer. It is interesting that these changes have been found by Auerbach[4] in the trachea, a rare site for invasive primary cancer.

Carcinoma in situ adjacent to invasive bronchogenic carcinoma or in the contralateral lung is being reported with increasing frequency.[4, 6, 9, 19, 29, 37, 38, 46, 49] Serial bronchial sections on specimens which contain bronchogenic carcinoma are

often found to contain a continuous transition from normal bronchial mucosa through basal cell proliferation and squamous metaplasia to carcinoma in situ adjacent to invasive cancer.[6, 19, 23, 35, 49] Invasive cancer of the lung may be the final stage of a maturation process beginning with metaplasia and carcinoma in situ, ending in invasion and metastasis.

The progression of in situ carcinoma to invasive cancer of the bronchus is probably similar to that in other organs, such as the skin, oral cavity, and cervix. For some reason this maturation does not appear to progress in all parts of the bronchial tree simultaneously. In the 2 cases presented, as well as in other documented reports,[36, 43, 49] one site in the bronchial tree seems to progress to invasive cancer months to years before other portions do so. Certain portions of the tracheobronchial system appear to have more of a predisposition to the development of cancer than others. For example, the trachea and middle lobe are uncommon sites of primary invasive carcinoma.

Further evidence for the multicentric origin of bronchogenic carcinoma is found in the reports of multiple microscopic invasive lung cancers that were noted at routine autopsy,[4, 17, 21, 32, 34, 42] as well as the cases listed in Table I.

The development of lung cancer in more than one location is not surprising if it is assumed that the bronchial tree is fairly uniformly exposed to various inhaled carcinogens. A statistical relationship between smoking and epidermoid carcinoma of the lung has been established.[2, 3, 14, 15, 50] Other substances suggested as agents related to lung cancer are the chromates, nickel, arsenic, and asbestos.[14, 48] The association of carcinoma of the larynx and bronchus lends support to the thesis of an inhaled carcinogen affecting the respiratory mucosa diffusely.[8] The larynx as well as the bronchus of the heavy smoker has been found to contain premalignant changes.[2, 3, 10, 20, 39] Certainly, there is some better reason than improved diagnostic acumen and rising population to account for the remarkable increase in the incidence of lung cancer.[14]

The "Recurrence" of Bronchogenic Carcinoma.—Pertinent to this discussion is the clarification of the term "recurrence." Anderson[1] has defined this as "a clinical term used to describe the reappearance of a tumor once it has been apparently removed or destroyed." Following *apparent* removal or destruction of tumor, extension, spread, or metastasis are commonly considered recurrences. A new or second primary cancer is an independent neoplasm that has originated at a site separate from another cancer.

It appears that some cases of recurrent bronchogenic carcinoma following an apparently successful pulmonary resection may not be a continuation of the original tumor, but a new primary cancer of the bronchus.

Following pneumonectomy or lobectomy for bronchogenic carcinoma, recurrence in the bronchial stump may be the result of extension of residual tumor in metastatic hilar lymph nodes or adjacent tissue. Without metastatic node involvement or residual tumor in tissue adjacent to the point of resection there should be some question whether a carcinoma found at the stump after a prolonged period represents recurrence of the original tumor or development of a new primary lesion in the bronchus, proximal to the line of resection. Bronchopleural fistula and empyema are the usual consequences if the amputation of

the bronchus is through tissue-containing carcinoma. After a prolonged interval, "recurrence" of carcinoma in the bronchial stump in a patient who had an uncomplicated pulmonary resection suggests the possibility of a new primary bronchogenic carcinoma, since carcinoma in situ is frequently noted in the bronchus adjacent to frank invasive carcinoma.

Following pulmonary resection, carcinoma in the bronchial mucosa of other parts of the lung may represent the development of a new primary lesion. Bronchial mucosa is an unusual site for metastasis.

DIAGNOSIS OF THE NEW PRIMARY BRONCHOGENIC CARCINOMA

If a second bronchogenic carcinoma is discovered after a prolonged interval in a patient who appeared to have had a successful operation for the original lung cancer, the possibility of a new primary tumor deserves consideration. It is possible in some cases that a resectable new primary cancer of the lung has been considered a hopeless recurrence of the original lesion.

Perhaps, in addition to interval roentgen studies, follow-up bronchoscopic examination at 6-month to 1-year intervals might be an aid in detecting small new primary lesions in the major bronchi. This would be particularly useful in patients treated by lobectomy for epidermoid carcinoma of the bronchus. Cytologic studies might suggest the presence of a bronchogenic carcinoma, but would probably be of little value in localizing a lesion not visible on x-ray films.

THE SURGICAL TREATMENT OF THE NEW PRIMARY BRONCHOGENIC CARCINOMA

If lobectomy has been the original procedure, further pulmonary resection for a second primary tumor may be possible. The scope of the operation would depend on pulmonary status, location, and extent of the lesion. A new primary bronchogenic carcinoma in a remaining ipsolateral lobe or main-stem bronchus could be treated by resection of the remaining lobe and main-stem bronchus.

If the second malignancy were located in the opposite lower or middle lobe, lobectomy or combined middle and lower lobectomy would be feasible. Involvement of the contralateral upper lobe at a point distant to the upper lobe takeoff could be resected by upper lobectomy. If the new primary lesion is dangerously close to the upper lobe orifice or actually involves the main-stem or intermediate bronchus, combined resection of the upper lobe and main-stem or intermediate bronchus with lower lobe transplant may be a feasible procedure.[45] In the patient with a small peripheral new primary lesion and pulmonary insufficiency, segmental or wedge resection might be the only applicable type of resection.

Following pneumonectomy, resection of a portion of the contralateral lung would probably have to be confined to segmental or wedge resection. If the second primary tumor were located in the middle lobe, admittedly a rare site, middle lobectomy might be tolerated.

In Case 1 an example of a segmental resection for a new primary bronchogenic carcinoma, performed 9 years after pneumonectomy, is described. This patient had unusually good pulmonary function following pneumonectomy.

Tracheostomy was probably a major factor in the uncomplicated immediate postoperative course.

A small new primary tumor of the bronchial stump could be removed by resection of the stump and adjacent trachea followed by plastic closure of the trachea.

In selected cases, lobectomy has been shown to be a sound operation for bronchogenic carcinoma and is being performed with increasing frequency.[7, 12] It is in this group that the possibility of surgical treatment of a second primary tumor is most promising. With increasing numbers of patients surviving pulmonary resection for long periods, the incidence of multiple lung cancer may increase and be successfully treated.

SUMMARY

Two cases of a second bronchogenic carcinoma developing 9 and 10 years after resection of the original primary bronchial cancer are presented. A table of reported cases of gross multiple primary bronchogenic cancer is included. Evidence for the multicentric origin of bronchogenic carcinoma is reviewed. The problem of differentiation between recurrent lung cancer and a new primary lesion is discussed. A proposed plan of follow-up of patients who have had an apparently successful operation for initial epidermoid carcinoma of the bronchus is outlined. Various methods of surgical resection for a second new primary bronchogenic carcinoma are suggested.

The precise identification and incidence of second primary bronchogenic carcinomas is not well established. It appears, however, that the problem of multiple bronchogenic carcinoma will become increasingly important.

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PRIMARY PULMONARY LEIOMYOSARCOMAS

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PRIMARY leiomyosarcoma of the lung is a rare tumor. However, since 1950, numerous reports of this neoplasm have appeared in the literature. Neuman[10] in 1938 reported 2 cases of primary pulmonary leiomyosarcoma diagnosed at autopsy. Ochsner[11] in 1958 published a case report of a patient for whom he performed a pneumonectomy in 1936 for a pulmonary leiomyosarcoma. The patient was well and working when last seen 21 years later. This case demonstrates the excellent prognosis in cases when the tumor is completely excised.

Within a 10-month period at Baylor University Medical Center, 2 cases of primary pulmonary leiomyosarcoma were diagnosed and the patients received surgical treatment.

CASE REPORTS

CASE 1.—F. B., a 60-year-old white man, was first admitted to Baylor University Medical Center on Feb. 6, 1958. For the preceding 5 to 6 months he had noted some shortness of breath which was aggravated by exertion. Three months prior to admission the patient experienced a severe respiratory infection accompanied by fever, chest pain, and purulent sputum. Following antibiotic therapy the symptoms receded, but increasing dyspnea, a 20 pound loss of weight, malaise, low-grade fever, and occasional hemoptysis persisted. The patient had been a heavy smoker for many years.

Physical examination revealed a suggestion of cyanosis of the head and neck, and the patient was moderately dyspneic while talking at rest. The thorax presented an increased posterior-anterior diameter and the breath sounds were distant throughout both lung fields consistent with moderately severe emphysema. In the base of the right lung there was an ill-defined area over which percussion was dull, breath sounds were muffled, and numerous crepitant and subcrepitant râles were heard. The liver and spleen were both palpable below the costal margins.

Roentgen examination of the chest revealed a large cavitary mass in the superior segment of the right lower lobe. Moderately severe emphysema was also noted on the chest films (Fig. 1).

On Feb. 7, 1958, a right thoracotomy was performed. After the chest was opened, a large mass was seen occupying the superior segment of the right lower lobe. The mass measured approximately 15 cm. in diameter and was attached to portions of the parietal pleura. A right pneumonectomy was contraindicated because of the poor respiratory status of the patient secondary to pulmonary emphysema. A right lower lobe lobectomy was

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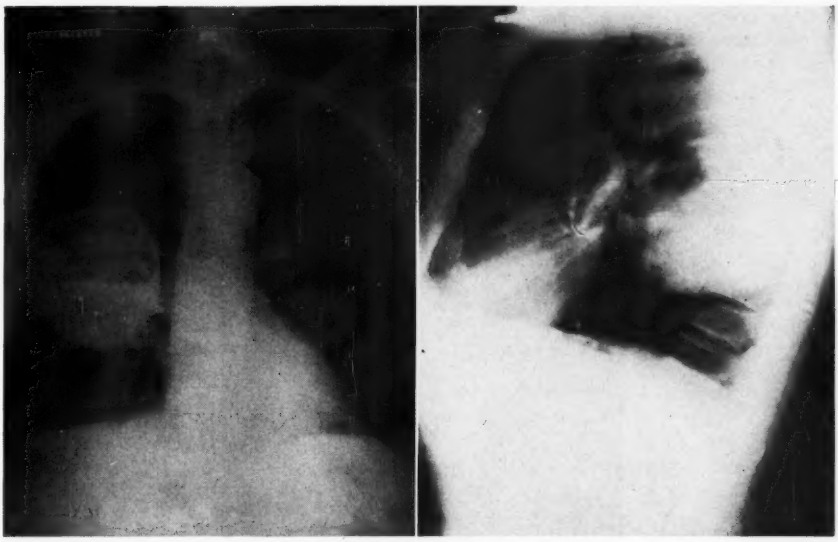

Fig. 1.—Case 1. Roentgenograms which illustrate a large cavitary lesion with an air-fluid level occupying the superior segment of the right lower lobe.

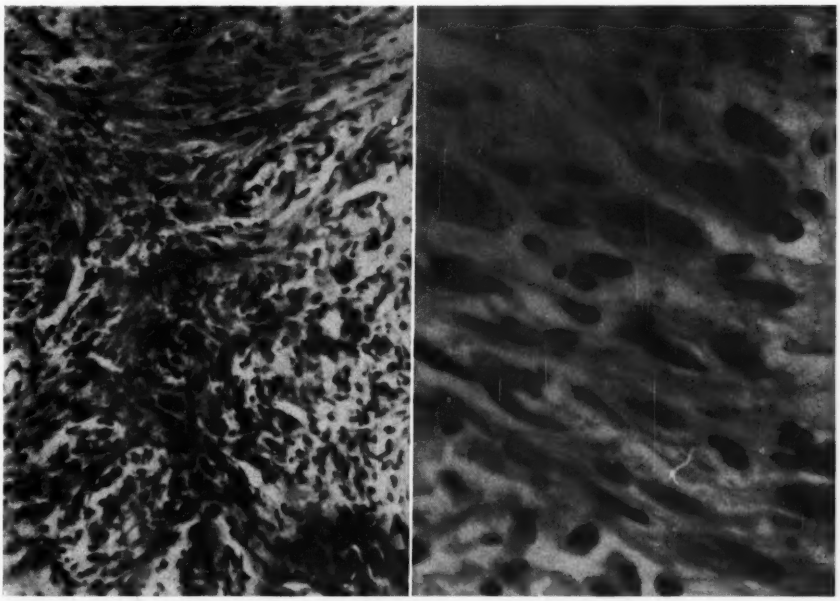

Fig. 2.—Case 1. Photomicrographs of the surgically removed specimen which illustrates fusiform cells with mitoses and varying degrees of anaplasia.

Fig. 3.—Case 2. Roentgenogram which illustrates a wedge-shaped atelectatic area in the left lower lobe with a suggestion of a mass at the apex of the consolidated area.

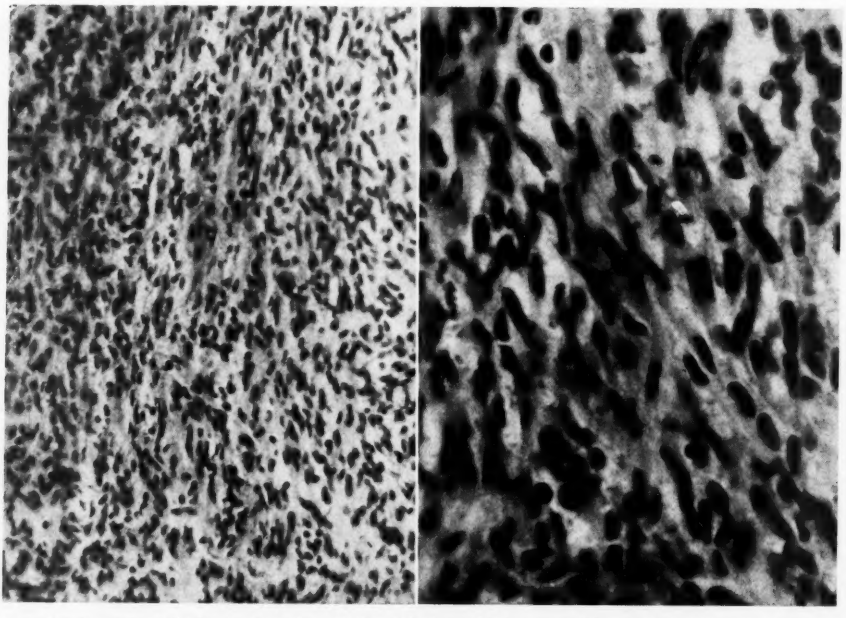

Fig. 4.—Case 5. Photomicrographs of the intrabronchial tumor illustrating diffuse sheets of spindle-shaped cells with increased chromatin and moderate pleomorphism.

performed after mobilizing the lobe in the extrapleural plane since the tumor was attached to the pleura. The proximal bronchus did not appear to be involved by the tumor and no gross involvement of the hilar or mediastinal lymph nodes was noted. Several large bullae in the right upper lobe were resected after completion of the lobectomy.

Pathologic Findings.—The surgical specimen contained a large cavitary mass measuring 13 cm. in diameter which was filled with necrotic, friable, gray-white, and pink tissue. Microscopically the tumor consisted of undifferentiated pleomorphic cells, most of which were fusiform in appearance (Fig. 2). The pathologic diagnosis of the surgical specimen was primary leiomyosarcoma of the right lower lobe.

Postoperative Course.—During the postoperative course he received 40 mg. of nitrogen mustard intravenously over a 4-day period. Since his cough was ineffective, he required numerous endotracheal aspirations. He was discharged on the eighth postoperative day. However, he was readmitted 5 days later with severe dyspnea and a temperature elevation of 103° F. Despite active therapy, his condition deteriorated rapidly with increasing dyspnea and he died approximately 12 hours after admission. An autopsy demonstrated severe vesicular and bullous emphysema and an organizing pneumonitis in the right middle lobe.

CASE 2.—A. E., a 42-year-old white man, was admitted to Baylor University Medical Center on Nov. 23, 1958. Intermittently, for 10 to 11 months, he had noted a "hacking, tight" cough and he had been hospitalized in January and February of 1958 for "pneumonia" with symptoms of fever, left chest pain, and cough. A weight loss of five to seven pounds was noted in the 2 months prior to admission. He had been a heavy smoker for approximately 22 years.

Physical examination revealed a thin, white man who appeared chronically ill. The breath sounds were decreased over the left lower lung field laterally, and inspiratory râles were noted over the same area. The remainder of the physical examination was not remarkable.

Roentgen examination of the chest, including stratigrams, revealed consolidation of a portion of the posterior basal segment of the left lower lobe. A suggestion of a mass was seen at the apex of the wedge-shaped consolidated area in the nine-centimeter sections of the stratigrams (Fig. 3). Pulmonary function studies revealed no gross abnormalities.

During the bronchoscopic examination on Nov. 24, 1958, a strawberry-like tumor was seen in the orifices of the bronchi to the anterior and lateral basal segments of the left lower lobe. Since this was thought to be a bronchial adenoma because of its gross appearance, no biopsy was performed.

On Nov. 26, 1958, a left thoracotomy was performed and an almost completely atelectatic left lower lobe was found. A left lower lobe lobectomy was carried out without difficulty. The patient had an excellent postoperative course and was discharged from the hospital on the sixth postoperative day.

Pathologic Findings.—One centimeter below the proximal end of the bronchial stump was a 1.5 by 1.2 cm. pinkish-gray, somewhat fleshy, firm mass which bulged slightly on the cut surface. Microscopically, the tumor arose from the wall of the bronchus and was composed of closely approximated, spindle-shaped cells that were arranged in diffuse sheets and interdigitating serpiginous cords. The nuclei demonstrated increased chromatin and moderate pleomorphism (Fig. 4). The pathologic diagnosis of the specimen was primary leiomyosarcoma of the left lower lobe of the lung.

DISCUSSION

Two additional clinical cases of primary leiomyosarcoma of the lung are reported bringing the total number of cases in the literature at the present time

to twenty-eight.[1-18] The average age of the patients was 44.3 years with the youngest patient 4 years of age and the oldest 83 years of age. The tumors have been reported in 12 females and 16 males.

The most frequent symptoms reported were cough, dyspnea, and chest pain. The latter symptom is interesting in that it did not preclude a good prognosis for the patient if the tumor could be completely removed at the time of surgery. Other less common symptoms were hemoptysis, weight loss, weakness, and fever.

Nine of the leiomyosarcomas arose primarily in the left lower lobe while eight arose in the right middle and lower lobes. One arose from the main-stem bronchus and two had their origin in the trachea. Five were located in the left upper lobe and two in the right upper lobe. Fifty per cent of the cases demonstrated definite bronchial sites of origin with many showing large intraluminal components as in the second case just reported.

Generalized metastases were noted in 6 cases, three occurring in patients treated surgically and the remaining three occurring in patients not receiving definite therapy.[1, 2, 4, 10, 12, 16] Local invasion involving the pleura, adjacent lobe, or the pulmonary vein and left atrium was seen in 5 cases.[7, 9, 15, 17] There is only 1 recorded case in which lymph nodes were involved with tumor and the lymph node involvement in this case was associated with generalized metastases.[4] One patient demonstrated signs and symptoms of Addison's disease 10 months postoperatively, and the autopsy revealed replacement of the adrenal glands by tumor as well as extensive metastases.[1]

Roentgen films of the chest and bronchoscopic examination are the principal methods of diagnosis of primary pulmonary leiomyosarcoma. The roentgenograms will show a mass in the lung field with rounded, fairly sharp edges. However, a definite diagnosis cannot be established from the films alone. Bronchoscopy with a positive biopsy is very helpful but, as noted previously, 50 per cent of the tumors do not have an intrabronchial component. Cytologic examination of the bronchial secretions is unrewarding since these tumors do not tend to exfoliate.

TABLE I. TYPES OF THERAPY

Pneumonectomy	10
Lobectomy	5
Refused therapy	3
Diagnosed at autopsy	3
Attempted pneumonectomy	2
Wedge or local incision	2
Tracheal resection	1
Radiation	1
Symptomatic	1

Treatment and Prognosis.—Surgical excision of the tumor and adjacent pulmonary tissue is the treatment of choice in all cases of primary pulmonary leiomyosarcoma. Table I lists the various types of therapy employed in the 28 cases reviewed. Pneumonectomy was the predominant type of therapy although the use of bronchoplastic procedures and lobectomy would preserve pulmonary

tissue and improve the quality of the patient's survival. Lobectomy is considered the best operative procedure when it is feasible since the tumors tend to remain localized and do not generally spread by lymphatic channels.

The long-term prognosis is excellent in patients in whom the primary tumor can be entirely resected. In the 18 cases in which operative removal of the tumor was accomplished, 12 of the patients were alive and well when reported from less than 1 month to 21 years following resection. One patient lived 6 years without recurrence and then died of a heart attack.[17] One patient died suddenly 2 months postoperatively; there was no autopsy.[1] Another, Case 1 from the present series, died on the thirteenth postoperative day of respiratory complications. Three patients who had recurrence of the tumor died from 4 to 18 months after the operative procedure.[1, 5, 12] Two patients died during the operation before the desired procedure could be accomplished. One patient died of cardiac arrest[17] and the other from bleeding into the opposite bronchus when a two-stage pneumonectomy was attempted.[13]

Sixty-three per cent of the patients with operation survived without tumor recurrence or complications of surgery; 16 per cent died with recurrences of the tumor; 10 per cent died during the operation, and 11 per cent died within 2 months of surgery from complications which may have been referable to the operation.

SUMMARY

Twenty-six cases of primary pulmonary leiomyosarcoma have been collected from the literature and 2 additional cases are reported in this paper.

The most frequent symptoms indicating the presence of this neoplasm are cough, dyspnea, and chest pain. Roentgen films of the chest usually reveal a rounded, fairly well-circumscribed mass in the lung field. However, a definite diagnosis cannot be made by roentgen films alone. Bronchoscopy with biopsy is helpful in establishing a preoperative diagnosis in approximately one half of the cases. Pulmonary resection for primary leiomyosarcoma of the lung should be conservative in type, conserving as much lung tissue as possible while removing the entire tumor with a moderate amount of surrounding normal pulmonary tissue. If primary leiomyosarcomas of the lungs are excised completely by pulmonary resection, an excellent cure rate may be expected.

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ELECTIVE TRACHEOSTOMY IN PATIENTS WITH RESPIRATORY INSUFFICIENCY WHO ARE SUBJECTED TO PULMONARY SURGERY

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PATIENTS with surgically amenable intrathoracic diseases have often been denied operation because of greatly diminished pulmonary function. The critical time for such patients is in the immediate and early postoperative period. An understanding of the pathophysiology during this critical period will lead to the application of surgical and therapeutic measures directed toward correction or, at least, control of those alterations.

PRINCIPLES

Respiratory acidosis usually is found at the completion of thoracic surgery performed under general anesthesia.[1-4] In the absence of previous respiratory embarrassment,[5] particularly when there was carbon dioxide retention,[6] the acidosis will be relieved by an increase in respiratory rate and dead space ventilation.[3] However, if these compensatory mechanisms to increase alveolar ventilation[7] be inadequate, the acidosis will deepen with rapidly falling blood pH, carbon dioxide narcosis, and circulatory failure.[8, 9]

The diffusibility of carbon dioxide is much greater than oxygen. Therefore, when ventilation is so severe as to prevent satisfactory CO_2 elimination, hypoxia will be marked. In the early postoperative period, diffusion of oxygen is always diminished[6, 10, 11] with low arterial oxygen tensions,[4, 12] even in good risk patients. The hypoxemia is aggravated and persists because of postoperative splinting, retained secretions, atelectasis and bronchospasm, and fever.[2, 13] If unchecked, it will eventuate in cerebral changes, which may be permanent,[14] and terminate in cardiac arrest.[15] Hypoxia due to diminished ventilation may be relieved successfully and readily by the administration of oxygen.[16] This form of therapy does not improve the existing hypoventilation, which then results in carbon dioxide accumulation to such an extent that it will no longer act as a drive on the respiratory center.[17] When a patient receives oxygen postoperatively, acute respiratory acidosis may be superimposed upon a chronic form, such as emphysema. Control of respiration shifts to the chemoreceptor

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response to hypoxia causing hypoventilation and further retention of carbon dioxide. Peters[18] has demonstrated that hypercapnia may produce bronchospasm, which further increases the hypercarbia. Hypercapnia, as a factor in the pathogenesis of cardiac arrest, has also been documented.[15, 19]

Preoperative evaluation of pulmonary function provides the surgeon with an index for anticipating difficulties which may ensue. Correctly appraised, the risk in patients with severe malfunction may be reduced to acceptability by careful preparation of the patient and planned utilization of various supportive adjuncts postoperatively.

Preoperative preparation of the thoracic surgical patient should include: (1) correction of blood volume and electrolytic imbalance, (2) control of infection, (3) drainage of the bronchopulmonary passages, (4) breathing and coughing exercises, and (5) psychological preparation. The extent of pulmonary function work-up should be proportional to the insufficiency evidenced by the patient; prolonged and/or more sophisticated studies need not be applied in all instances.[7, 16, 20]

Various modalities which may be utilized postoperatively in patients having borderline pulmonary and/or cardiac function have been described: (1) inspiratory assistors, (2) cough assistors, (3) elective tracheostomy, (4) transtracheal respirators,[7, 21, 22] and planned corticosteroid therapy.[13, 22]

TRACHEOSTOMY

Tracheostomy is an ancient operation. Asclepiades, in 124 B.C., was the first to discuss the possibility of relieving upper respiratory obstruction by this procedure; Brasavola is credited with performing the first authentic operation in 1546.[23] Until recent years, tracheostomy was used only for organic (physical) high obstruction. Its therapeutic values now have broadened in scope, but still are directed, in major degree, toward relief of obstruction.

The advantages afforded are:

1. *Maintenance of tracheobronchial toilet:* In 1938, Haight[24] described nasotracheal catheter suction as a means of avoiding postoperative complications incident to retained intratracheobronchial secretions. However, he has stressed that adequate toilet by this means can only be maintained when a house-officer is in constant attendance.[25] Thoracic surgery is now being performed widely in community hospitals where such extravagant care often is not available. Tracheostomy provides a ready access to the tracheobronchial tree and may be managed by trained nursing personnel.

2. *Alleviation of physiologic obstruction:* Tracheostomy affords relief of physiologic obstruction: dead space is diminished by 100 ml.[9] and resistance to expiration and inspiration is reduced,[26] thereby materially improving alveolar ventilation[27] and elimination of carbon dioxide. Oxygen may be provided unopposed and accurately in desired concentration, volume, and pressure through the use of various ventilators or respiratory assistors. Indeed, respiration may be completely controlled.

3. *Provision for topical medications:* Occasionally, topical medications are indicated. Tracheostomy provides a ready means for administration in accurate dosage.

4. *Cardiovascular changes associated with respiratory obstruction:* Long-standing respiratory obstruction results in changes in intrathoracic pressures[28]; for example, expiratory obstruction of emphysema causes an increase in intrapleural pressure leading to reduction in venous return to the heart. Tracheostomy relieves the obstruction in part. Artificial ventilators, particularly those with a negative phase, further improve ventilation as well as cardiac function.[7, 21] Spencer and his associates[22] have reported that anoxia markedly increases pulmonary vascular resistance, especially in those patients with pulmonary hypertension.

The question arises as to indications for performing tracheostomy in the postoperative patient. Björk and Engström[9] advise tracheostomy when the arterial pCO_2 rises over 70 mm. Hg. It is well known that there are no reliable signs of carbon dioxide retention during operation or during the early postoperative period,[3, 29, 30] when the classically ascribed findings are masked by blood volume and electrolyte changes, stress reaction, metabolic and hormonal alterations, administration of narcotics and other drugs. There are factors other than hypercapnia which would lead one to tracheostomy, such as recurrent atelectasis, failure to maintain adequate tracheobronchial toilet, debility; however, in the final analysis, the indication is based largely on clinical judgment. In the patient having greatly diminished pulmonary function preoperatively, the margin of error in this judgment is severely narrowed. Planned elective tracheostomy reduces the risk. Supportive measures, as indicated, may be provided with a minimum of difficulty at any time—even prophylactically. Björk and Hilty[6] have presented 3 postoperative cases of patients with CO_2 tensions ranging from 95.6 to 124.5 mm. Hg, who were subjected to tracheostomy. All 3 patients died shortly thereafter; arterial pCO_2 level in one had dropped to 35 mm. Hg. This example demonstrates the value of tracheostomy but also that delayed operation may allow irreversible changes to be established which will lead to death.

Elective tracheostomy has other advantages. It may be performed unhurriedly, with attention to detail. The patient may be apprised of the procedure preoperatively, thereby being psychologically prepared for those changes inimicable to tracheostomy.

There are disadvantages and complications attendant upon tracheostomy, the most important of which is that the procedure is performed too late, in a panic, in a moribund patient. Other complications include: tracheitis, hemorrhage, mediastinal emphysema and pneumothorax, stenosis, movement of the tube which can lead to ulcerations, fistula, and mediastinitis (see Case 9).[31-33] Almost all complications can be avoided. Usually, following removal of the tube, the wound heals with a cosmetically acceptable scar, especially when a horizontal skin incision is employed.

PLAN OF STUDY

During the past 5 years, the great majority of patients coming to elective pulmonary surgery at Kings County Hospital, Division I, have been subjected to pulmonary function tests. All patients with tuberculosis have been evaluated by this means. This study comprises all patients undergoing surgery of the lung subjected to planned elective tracheostomy. In 6 patients the major disease was tuberculosis; bronchiectasis, emphysematous bullae, and carcinoma accounted for 3; which makes a total of 9 patients. An additional case is presented as a control (Case 10).

All patients were subjected to pulmonary function tests at the time they were considered to be optimally prepared for surgery. Bronchodilators were not administered in conjunction with performance of the tests; however, bronchodilators were not discontinued in those patients receiving them as part of their therapy. In 4 patients the tests were repeated because of suspected error and were found to change only minimally. Differential bronchospirometry was determined in 6.

A standard tracheostomy was performed after closure of the thoracotomy incision and repositioning of the patient supine, still under anesthesia, with endotracheal tube in place. Tracheostomy tubes were of the commercial metal types, sizes No. 8 and No. 9. All operations were performed by residents on the Thoracic Surgical Service. Tables I and II provide a summary of cases.

TABLE I. SUMMARY OF CASE REPORTS

CASE NUMBER	AGE	DISEASE	OPERATION	RMV	TV	VC (%)	MBC ACT.	MBC (%)	TVC (1-3 SEC.)	SURVIVAL
1	37	Tuberculosis	Rt. pneumonectomy	8.50	500	63	62	45	61-78-85	Living
2	23	Tuberculosis	LU lobectomy	7.55	479	46	36	37	70-84-92	Living
3	37	Tuberculosis	Rt. pneumonectomy	12.40	770	56	40	32	45-57-71	Living
4	24	Tuberculosis	Plombage thoracoplasty	9.35	519	49	54	43	54-76-86	Living at 14 mo.
5	50	Tuberculosis	Rt. pneumonectomy	6.90	625	91	82	75	60-73-79	1 da.
6	30	Tuberculosis	Thoracoplasty	7.80	355	45	47	41	58-78-88	Living
7	53	Bronchogenic Ca., tuberculosis	Rt. pneumonectomy	7.55	1,079	99	70	63	50-67-76	20 da.
8	34	Bronchiectasis	L. pneumonectomy	7.80	459	28	37	34	62-85-94	Living
9	58	Emphysematous bullae	RU lobectomy and excision bullae, RML and RLL			38	39	45	48-69-82	20 da.
10	51	Tuberculosis	Rt. pneumonectomy	9.00	484	65	50	50	30-66-75	5½ mo.

TABLE II

CASE NUMBER	OPERATION	MBC (% PREDICTED)	O_2 UPTAKE (CONTRALATERAL LUNG)	"ESTIMATED POSTOPERATIVE MBC" (CONTRALATERAL LUNG)
1	Pleuropneumonectomy	45	75%	34% (35%†)
3	Pleuropneumonectomy	32	100%	32% (27%†)
5	Pneumonectomy	75	60%	45%
7	Pneumonectomy	63	60%	38%
8	Pneumonectomy	34	100%	34%
9	Upper lobectomy and excision bullae, RML and RLL	45	80%*	36%
2	Lobectomy, left	37	80%*	29%
6	Thoracoplasty, 5 rib	41	80%*	33%
4	Plombage, thoracoplasty	43	60%	25%
10	Pneumonectomy	50	90%*	45%

*Conservative estimate; no actual bronchospirometry.
†Actual measurement made postoperatively.

Postoperatively, patients were provided with oxygen by catheter (4 to 6 L. flow) and aerosol detergents and bronchodilators. Corticosteroids were administered when necessary. Respirators and respiratory assistors were not utilized. Blood volume was sustained by clinical manifestations and hematocrit determinations.

Four case reports are presented in detail to illustrate the plan of treatment.

CASE REPORTS

CASE 3.—L. G. was a 37-year-old male Puerto Rican with a 20-year history of tuberculosis. Bacteriologic studies had been negative for 9 months. The electrocardiogram was normal. Pulmonary function 2 months prior to surgery (delay not for medical reasons): respiratory minute volume—12.4 L.; total volume—770; vital capacity—56 per cent of normal; maximum breathing capacity—40 L. or 32 per cent of predicted; timed vital capacity—45-57-71 per cent (1-3 sec.). Differential bronchospirometry revealed no function in left lung. On March 7, 1956, the patient was subjected to left pleuropneumonectomy and tracheostomy. He required oxygen continuously in the first 4 days. Attempted plugging of the tube resulted in cyanosis; the tracheostomy tube was left in place until May 26 (2½ mo. postop.). Ten days after operation he developed tachycardia, inspiratory râles, apprehension, and hypotension. He responded promptly to intravenous corticosteroids, 100 mg. Again an attempt was made to wean the patient from the tracheostomy tube; on March 24 he had a repetition of tachycardia, apprehension, and hypotension, but more severe. Chemical studies revealed acidosis. There was no response to infusion of neosynephrine. Consequently he was given 200 mg. of corticosteroids intravenously, in addition to norepinephrine. Lethargy progressed to coma which persisted 2 days and was associated with bizarre neurological signs (spinal tap normal). Cortisone acetate, 200 mg., was administered daily intramuscularly. By March 31 the sensorium was fairly clear and recovery seemed complete. Gradually the cortisone dosage was reduced so that by April 19 he was receiving only 50 mg. daily, in addition to 25 mg. ACTH weekly. However, on April 21, a similar episode, somewhat less intense, of hypotension, stupor, bizarre neurological signs, and inspiratory râles recurred. Cortisone was administered promptly with rapid response. The intramuscular dosage of cortisone acetate was begun at 300 mg. daily and very gradually reduced so that on June 6 (2 mo. later) the dosage was 50 mg. daily. A change was made to prednisone, 20 mg. daily, and continued until August 16 and then reduced gradually and discontinued on August 20. ACTH was administered, 25 mg. weekly, from April 21

until August 20. After the acute episode on April 21, the patient's course was uphill. Postoperative chest films were entirely normal throughout the course. In October, examination for Addison's disease was negative. Pulmonary function 4½ mo. after operation: vital capacity–44 per cent; maximum breathing capacity–27 per cent predicted. Bacteriologic studies remained negative. The patient was discharged on Oct. 30, 1956.

This case demonstrated the most classical advanced signs of acute ventilatory insufficiency and carbon dioxide retention we have encountered in any patient who survived. The excellent response was ascribed to tracheostomy, oxygen, and to corticosteroid therapy. Late studies revealed no evidence of adrenal insufficiency of a permanent nature. The concurrent findings of CO_2 retention and râles would suggest that bronchospasm played a significant role and responded well only to corticosteroids, as has been pointed out by Peters[18] and Sealy and his co-workers.[5, 13]

CASE 4.—L. B. was a 24-year-old Negro man known to have had tuberculosis for 5 years. During the 2 years before the present operation, he had undergone left extrapleural plombage followed by a 7-rib staged thoracoplasty. Subsequently, a 3 cm. cavity appeared in the right upper lobe of the lung. Bacteriologic studies demonstrated resistant organism. The electrocardiogram showed right axis deviation. Pulmonary function tests 8 days prior to present operation (there had been 4 in the previous 2 years): Respiratory minute volume—9.35 L.; total volume—519 c.c.; vital capacity—49 per cent normal; maximum breathing capacity—54 L. or 43 per cent predicted; timed vital capacity—54-76-86 per cent (1-3 sec.). Differential bronchospirometry: right lung—O_2 uptake 49 per cent; ventilation 63 per cent (repeated and corroborated; angiocardiogram normal). On May 29, 1956, he was subjected to right extraperiosteal plombage, effecting satisfactory collapse, and tracheostomy. The postoperative course was relatively smooth, however, the tracheostomy remained patent and he could not tolerate operative closure long. Bacteriologic studies did not change. The electrocardiogram 5 mo. after operation showed right ventricular strain. He signed out against advice July 13, 1957, a pulmonary cripple.

This case illustrates the progressive nature of tuberculosis despite intensive medical and surgical therapy. Plombage thoracoplasty results in the least impairment of ventilation, early,[34] which was an indication for its choice. The postoperative insufficiency was enough to necessitate more or less permanent tracheostomy and the development of cor pulmonale.

CASE 9.—F. D. was a 58-year-old white man with bullous emphysema and giant bulla of the right lung. The electrocardiogram showed right ventricular hypertrophy. Pulmonary function 2 months preoperative: Vital capacity—38 per cent of normal; maximum breathing capacity—39 L. or 45 per cent predicted; timed vital capacity—48-69-80 per cent (1-3 sec.); residual volume—156 per cent; residual volume/total lung volume—64 per cent (predicted 20 per cent); pulmonary clearance delay—343 per cent. Bronchospirometry was not done. On Oct. 6, 1959 he was subjected to right upper lobectomy and plication of bullae of the RML and RLL and tracheostomy. Twelve days postoperative there was evidence of a small bronchopleural fistula; easily controlled by tube thoracostomy. Progressive pulmonary insufficiency became apparent together with febrile reaction. He died 19 days after operation. Autopsy revealed dislodged tracheostomy tube, posterolateral tracheal fistula, and extensive mediastinitis.

This case demonstrates, first, the advantage of tracheostomy and, subsequently, a hazard of that operation. This case also represents the only incidence

of significant complication of tracheostomy we have encountered in 5 years, elective or emergency. It suggests that a sense of overconfidence may lead to neglect with disastrous results.

CASE 10.—C. J. was a 51-year-old white man with a 4-year history of tuberculosis. Bacteriologic studies revealed: resistant organism. The electrocardiogram was normal. Pulmonary function one month before operation: Respiratory minute volume—9 L.; total volume—484 c.c.; vital capacity—65 per cent of predicted; maximum breathing capacity—50 L. or 50 per cent predicted; timed vital capacity—30-66-75 per cent (1-3 sec.). Bronchospirometry was not done. On Nov. 5, 1958 he was subjected to right pneumonectomy; tracheostomy had been planned but was not performed. About 60 hours after operation he was found in shock with atrial fibrillation. He responded to tracheostomy, norepinephrine, intravenous corticosteroids, and rapid digitalization. The postoperative tachypnea and restlessness were relieved. After 2 days, the intravenous corticosteroids were changed to prednisone, 15 mg. daily, and the norepinephrine discontinued. An attempt was made to discontinue prednisone therapy early (history of ulcer diathesis) and also to plug the tracheostomy. This resulted in prompt appearance of acute respiratory acidosis, this time corroborated by laboratory studies. Thereafter, steroids were gradually reduced and the tracheostomy tube was plugged gradually. The patient was up and about 8 weeks after operation, without evidence of respiratory insufficiency. He signed out of the hospital against advice 4 months following surgery. Ten days later he was readmitted with pulmonary insufficiency and pneumonitis in the remaining lung. Tracheostomy, steroid, and digitalis therapy were necessitated; together with large doses of antibiotics. The patient died 6 weeks later with lobar pneumonia and cor pulmonale (corroborated by autopsy).

This case is presented as a "control." Elective tracheostomy had been planned, but through error was deferred. That it was indicated is apparent by the immediate postoperative course, even if the preoperative function tests are ignored. It would be conjectural to suggest that the course, in the long-term, would have been altered had the elective tracheostomy been performed. Certainly the early postoperative period would have been less hectic.

DISCUSSION

In surgery of the lung, some effort must be directed toward evaluation of pulmonary function. Sole reliance on patient history and physical examination is hazardous. The maximum breathing capacity has been the most valuable simple, single test of function, in our experience, despite its inherent inaccuracies.[16] Fortunately, error is reflected as diminished calculated function—not as an overestimation. Pulmonary function also may be based on the response of arterial pO_2 and pCO_2 levels to exercise.[20]

In 1957, Björk and Engström[7] presented a series of poor risk patients subjected to various forms of pulmonary operations. Preoperative maximum breathing capacity values in males ranged from 36 to 133 L. per minute. (In the three group categories the mean maximum breathing capacity was 77, 66, 83 L./min.) Sealy and his associates,[13] in 1960, presented a series of patients who had undergone various intrathoracic operations. Those in two categories, subjected to pulmonary surgery, were treated with steroids before and after operation; 5, all males, had recordings of lung function tests preoperatively and 4 of these

were subjected to elective tracheostomy. The maximum breathing capacity values ranged from 28-64.7 per cent of predicted capacity (avg. 46.6 per cent); there were no deaths.

Our series consists of 9 patients who underwent various pulmonary operations combined with elective tracheostomy; one other case is added as a control (Case 10), in which tracheostomy was performed 2 days postoperatively. There was only one female. Preoperative maximum breathing capacity values in the males ranged from 37-82 L. per minute (avg. 53.5 L.) or 32-75 per cent of predicted capacity (avg. 48.5 per cent). All patients were considered to be poor risk from the standpoint of lung function alone; 3 patients (Cases 1-3) had been denied surgery at some time previously because of greatly diminished function. Subsequently, taking into consideration the advantages which tracheostomy affords, a decision was made to offer these patients the surgery indicated for their disease, but to provide a safety valve for the critical early postoperative period by performing elective tracheostomy.

Postoperative risk in the thoracic surgical patient is determined by several factors: age, general health, cardiovascular status, type and pathogenesis of the disease process, anticipated magnitude of surgery, frequency of complications, as well as pulmonary function. Esophageal and cardiac surgery present special problems not directly related to preoperative pulmonary function.[10, 22, 25] In these cases, we also have utilized elective tracheostomy, both with and without artificial ventilation; not relying on lung function values.

A minimum criterion for planning elective tracheostomy may be based on the cases we have described. We have correlated the per cent of oxygen uptake of the contralateral lung, as determined by differential bronchospirometry, to the maximum breathing capacity, in per cent of predicted values. Multiplying these two values, we arrive at an "estimated postoperative maximum breathing capacity" which may exist immediately after surgery in the contralateral lung. In the 2 patients having postoperative function studies (Case 1 and 3), this figure correlated well (see Table II).

We do not presume that our "estimated postoperative maximum breathing capacity" is an accurate value in all patients; there are too many variables. However, it has been helpful to us as an index for planning tracheostomy in the patient whose lung function is reaching critically low levels.

Corticosteroids are an indispensable therapeutic adjunct in the postoperative period as evidenced by Cases 3 and 10. Our experience with combined pre- and postoperative use of the drug is limited, in this series, to Case 8.

Mechanical ventilators have not been employed in any of our pulmonary resections. We do not deny their value; indeed, their use will extend surgery to patients crippled to a greater degree than those in our series. However, prophylactic tracheostomy may obviate the necessity for such mechanical appliances.

There may be some question of the justification of substituting respiratory insufficiency and cor pulmonale for possible eradication or control of disease. Two patients (Cases 8 and 9) had cor pulmonale preoperatively and 2 others

(Cases 4 and 10) developed it postoperatively, one of whom died during a subsequent early readmission (Case 10). Three patients died during the initial hospitalization (Cases 5, 7, 9) of complications directly related to the operative procedure. One (Case 10) died later (5½ mo.) primarily because of cor pulmonale and pulmonary insufficiency. Four patients are living and well; a fifth is living but the status is not known (Case 2). One was lost to follow-up (Case 4), 14 months after surgery.

SUMMARY

A series of 9 patients with greatly diminished lung function, who were subjected to various types of pulmonary surgery and concurrent prophylactic tracheostomy, have been presented.

Planned, elective tracheostomy is a valuable adjunct in thoracic surgical patients, particularly for those in whom postoperative respiratory problems are anticipated. Carefully managed, it is a safe procedure and does not contribute to morbidity.

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ASSISTED CIRCULATION

I. The Arterial Counterpulsator

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IN THE PAST, therapeutic assistance to the failing left ventricle has been variously provided. Coronary vasodilator drugs have been used to improve coronary artery circulation. Cardiotonics and digitalis have improved the action of heart muscles. Fluid restriction and reduction of blood volume have been helpful. Finally peripheral resistance has been altered by vasopressors in hypotension and vasodilators in hypertension.

Recently, extracorporeal cardiopulmonary bypass has been used to treat myocardial failure.[1, 2] These procedures have transported systemic venous blood to the arterial tree, bypassing the lungs, with or without oxygenating the blood prior to its return to the aorta.

The importance of the pressure work of the heart has received further emphasis by the recent work of Sarnoff, Braunwald, and co-workers[3] who have stated that myocardial oxygen consumption depends mainly on the total integrated pressure and its duration (time-tension index) developed during systole and apparently bears less relation to cardiac output.

It appeared likely that if a quantity of blood was withdrawn from the arterial system, at or immediately following the normal instant of isometric contraction, the pressure required in the phase of the maximal rate of ejection

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These principles and this equipment were discussed at the Third World Congress of Cardiology, Brussels, Belgium, September 16, 1958.

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would be reduced considerably. If this same quantity of blood was returned during diastole to effect a mean pressure as great as the control pressure, the absolute perfusion would be equal. The coronary artery perfusion relative to the decreased myocardial work would be enhanced.

This communication describes a proportioning pump* placed on the arterial side of the circulation and its use in altering the pressure profile of the left intraventricular aortic and arterial pulses. Tracings recorded during experiments indicate that by appropriate timing of the rapid action of this pump the pressure work of the heart of the experimental animal has been reduced. At the same time, by increased diastolic blood pressure the mean pressure of the cardiac cycle has been sustained and tissue perfusion potentially increased. The result sought is normal or increased perfusion of the total organism with less cardiac work.

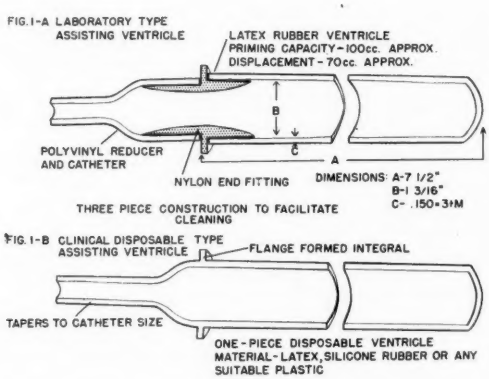

Fig. 1.—Details of laboratory and clinical type ventricles.

The anticipated clinical usefulness of this unit is to restore cardiac compensation by means of a limited surgical procedure involving exposure of the blood while outside the body to a small surface area of nonbiologic material and minimal physical and biochemical injury.

MATERIAL

The pumping equipment used in these experiments may properly be divided into three separate components: the ventricle (Fig. 1) which pumps the blood and receives it; the actuator (Fig. 2) which effects the proper motion of the ventricle; and the electronic power supply (Fig. 3) which controls and synchronizes the actuator with the patient's stimulus (e.g., the QRS of the electrocardiogram or the impulse of the cardiac pacemaker).

I. *The Pump.*—The *ventricle* (Fig. 1) is a smooth surface polyethylene tube, 7.50 inches long and 1.19 inches in inside diameter, with a wall thickness of 0.150 inch and a capacity of 100 ml. It is capable of discharging a maximum

*Manufactured by the Davol Company, Providence, R. I.

of 70 ml. per stroke. The ventricle is closed at one end. The other end is filled to a bell-shaped reduction of similar material that tapers to an internal diameter of 0.375 inch (3/8 inch). This connects to the arterial cannula. There is no valve. This ventricle alternately receives and ejects blood through one end.

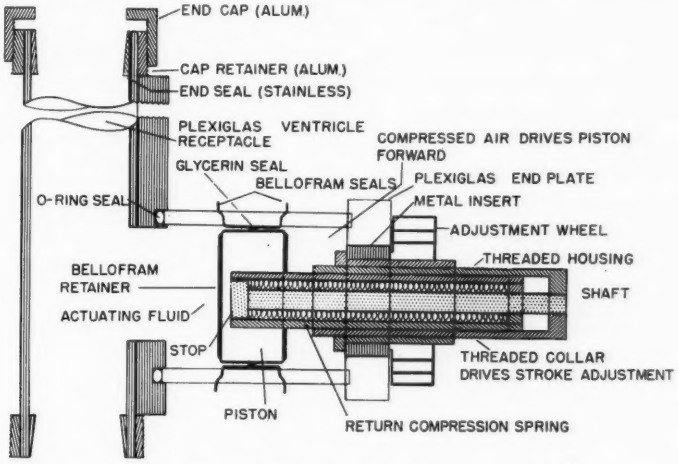

Fig. 2.—Diagram of the actuator.

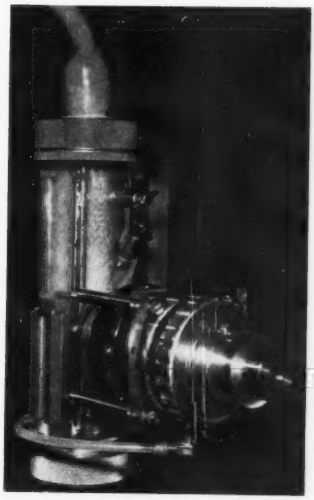

Fig. 3.—The actuator with assisting ventricle in the Plexiglas receptacle.

The *actuator* (Figs. 2 and 3) holds the ventricle and the propelling mechanism (see appendix). A pneumatically driven piston moves liquid to compress the polyethylene ventricle at regulated stroke volumes. A spring withdraws the piston rapidly, obligating refill of the plastic ventricle without dependence upon pressure from the arterial system.

The electronic power supply (Fig. 4) provides a control for the actuator which may be synchronized by the electrocardiogram to the hydraulic (hemodynamic) events of the cardiac cycle. A solenoid valve regulates the actuator and is controlled by a time delay network and a variable duration circuit.

The assembled unit is shown (Fig. 5).

II. *Experimental Procedure.*—Mongrel dogs were anesthetized with pentobarbital sodium using a dose of 30 mg. per kilogram of body weight. Electrocardiogram leads were applied. An intradermic polyethylene tubing PR 160 (0.045 inch in internal diameter) was inserted into the left ventricle via a carotid artery and similar tubing was passed to the root of the aorta to record pressure contours. The pressures within the pump ventricle and in the delivery

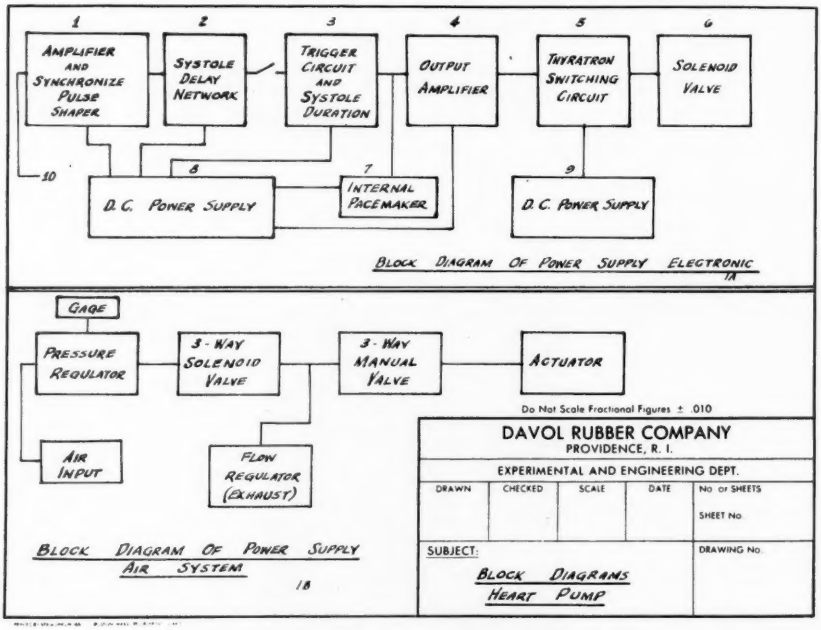

Fig. 4.—Circuiting of electronic power control.

catheter were recorded simultaneously with cardiac and aortic pressures on a Sanborn Twin-Viso recorder from Lilly capacitance manometers. An electrocardiogram from the animal or an impulse from a cardiac pacemaker was recorded simultaneously. The pacemaker was used in instances of surgically induced heart block in dogs.

The pump ventricle with its tubing and connectors was filled with saline solution or heparinized whole blood. The femoral artery, the iliac artery, or the left subclavian artery were isolated as the sites of cannulation of the aortic arterial tree. After cannulation and activation of the pump, that fraction of the content of the pump's ventricle represented by the stroke volume was exchanged with intra-aortic blood at each stroke (Fig. 6).

Initially, the effects of spontaneous heart rate and the pump upon pressure contours were observed. The pacemaker controlled the heart rate and the pump rate synchronously at predetermined rates while studies were made of other variables. The purpose of the experiment was to decrease the animal's intraventricular systolic pressure by providing a low peripheral resistance at the time of the cardiac systole while maintaining a body perfusion through a pump systole altering the animal's diastolic period. Recordings were made of the pulse contours while varying the pump delay, systolic duration, and diastolic duration in relation to the heart's electrical and hemodynamic events.

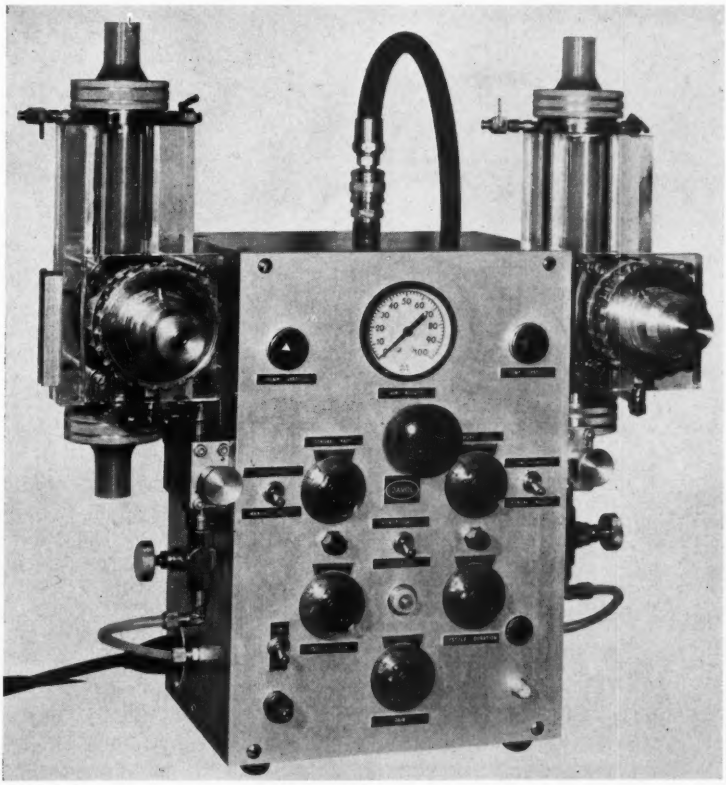

Fig. 5.—The electronic control box with actuator and ventricles assembled. The Davol proportioning pump.

RESULTS

I. *Pump Performance.*—

A. *Electronic circuit* (see Fig. 4): The electrical events were timed on an oscilloscope. The time delay network* is controllable from 0.05 to 0.6 sec. Systolic duration may be varied from 0.15 to 0.6 sec. The duration of diastole

*For technical explanations, see appendix.

is the remainder of the pump "cardiac cycle." The electrical output of the electrocardiographic machine (1.5 volts) is sufficient to trigger the pump mechanism.

B. *Hydraulic events of the ventricle and pump:* Tracings of pressures recorded from within the plastic ventricle resembled sine waves. The period of maximum rate of ejection did not exceed 0.20 sec. but can be regulated by the induced air pressure. The peak positive pressure was noted to be less than 300 mm. Hg and no negative pressure was recorded. The diastolic filling of the artificial ventricle can be regulated by an air escape valve.

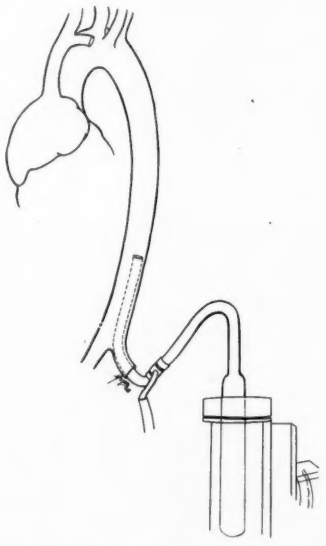

Fig. 6.—Diagrammatic representation of relation of counterpulsation to the circulation.

II. *Biologic Response.*—

A. *Pressure:* 1. Synchrony. The greatest and most consistent relief of heart work and the highest diastolic perfusion pressure are potentially achieved by synchronous events within the heart and the mechanical pump. As the heart is ejecting blood, the pump is aspirating blood. The hydraulic effect is low peripheral resistance (and low systolic aortic pressure) and rapid emptying of the left ventricle (short systolic time).

Figs. 7, 8, and 9 demonstrate the theoretically ideal type of pressure profile induced by the synchronous pumping technique as described and its attainment. These major alterations of pulse contour should represent major changes in heart work. There is an intraventricular pressure reduction of about 50 per cent during systole when, by ideal timing, pump diastole relieves left ventricular pressure. Diastolic pressure is increased up to 100 per cent and the mean pressures of the cardiac cycle are unchanged.

2. Asynchrony. It may be noted that there are many degrees of the action of the pump and the animal heart being out of phase. The pressure effect is additive or neutralizing to variable extents (Figs. 10 and 11).

B. *Heart work:* Intraventricular pressure and its duration are most closely related to heart work. While cardiac output was not assessed in these experiments, another series using Fick dye dilution and direct flow meter determinations is being conducted and is the subject of a second communication. Analysis

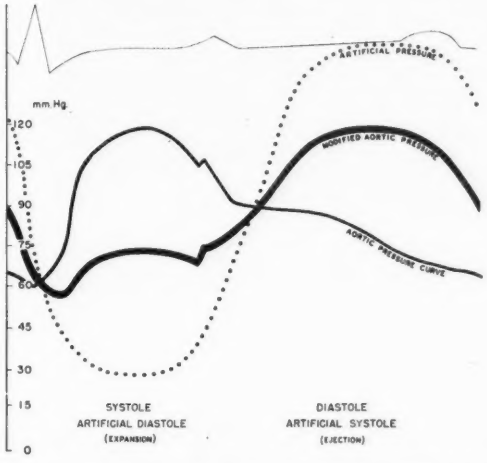

Fig. 7.—Modification of the aortic pressure curve by the arterial counterpulsator.

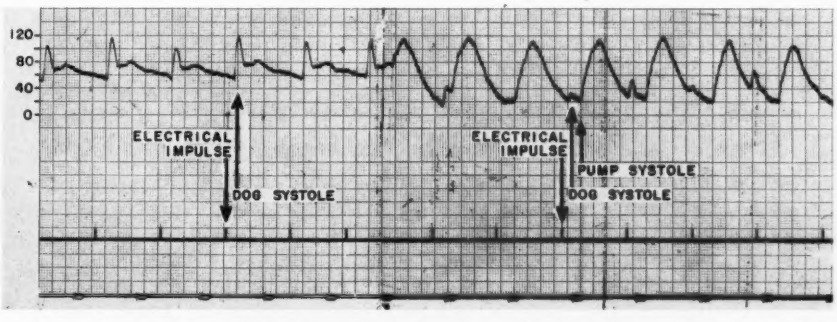

Fig. 8.—Synchronized artificial ventricle. Experimental heart block preparations. Cardiac systole initiated by cardiac pacemaker. Pump systole initiated by pacemaker with delay to place pump systole in cardiac diastole.

of the coronary artery flow and oxygen extraction by measuring coronary flow and A-V difference is also being carried out.

Wiggers[4] has stated that the mechanical energy of the heart is dissipated in ejecting the stroke volume of blood into the aorta against resistance and in imparting movement to the blood stream. The equation to calculate the work is

Fig. 9.—Synchronized artificial ventricle. Intraventricular and aortic pressures in a laboratory animal before, during, and after arterial counterpulsation. Assistance occurs between points marked by asterisks. Note fall in intraventricular pressure to approximately one half of unassisted level. Aortic pressure is reduced during cardiac systole by pump aspiration and augmented during cardiac diastole by pump injection. All pressures return to normal levels after assistance discontinued.

$W = QR + \frac{mv^2}{2}$. Q = volume of systolic discharge; R = resistance or mean arterial pressure; m = mass of ejected blood; v = average velocity.

Under basal conditions in human circulation, average values might be: Q = 60 ml., R = 100 mm. Hg, and v = 500 mm./sec. Therefore, in a normal heart at a rate of 72 per minute, the calculated work would be about 6 kilogram meters per minute.

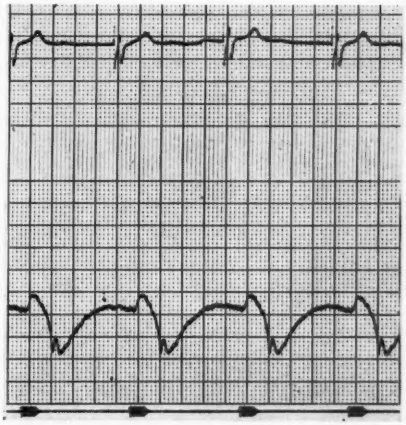

Fig. 10.—Improper synchronization of artificial ventricle. Pump injection occurs during late cardiac diastole and early systole. Cardiac ventricular contraction is opposed by pump injection.

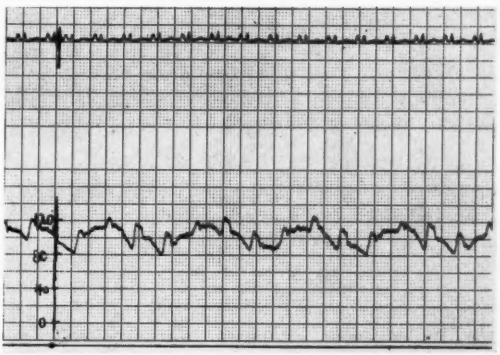

Fig. 11.—Asynchronous artificial ventricle. Pump injection is at slower rate than cardiac cycle. There is random assistance and opposition to cardiac systole.

If the mean arterial pressure is reduced to half its normal value during systole, with other factors kept constant, the calculated work would fall to half its normal value, that is, to 3 kilogram meters per minute.

C. *Resistance:* An analysis of tracings of pressures within the mechanical ventricle and the animal's ventricle (and intermediate points in the aorta and

tubing) illustrates the extent of pulse-damping by the resistance and resonance of the tubing. These results form hydraulic phenomena such as those that occur when the animal's pulse and mechanical forces are out of phase. It is apparent that alterations in pulse wave transmission rate require different timing of countercycling of the pump. This transmission time varies not only with pressure, volume, variable diameter, vascular and other factors but with the anatomic site of the counterpulsator cannula. The delay and duration controls readily permitted adjustment to the optimal pattern of pulse contour.

D. *Hemolysis:* To study hemolysis, 1,250 ml. of fresh whole canine blood was pumped through a tapered catheter with an orifice comparable to a 16 Fr. tip into a readily collapsible plastic blood bag under 100 mm. Hg pressures at 37° C. A unidirectional flow rate of 4,000 ml. per minute was achieved with a stroke volume of 50 ml. at a rate of 80 per minute. After one hour of pumping, the maximum plasma hemoglobin concentration was 50 mg. per cent. There were separate samples of blood taken from within the reservoir and from within the ventricle throughout.

SUMMARY

It has been possible to develop the pump and the electronic control system and to arrive at a point of altered pressure profile in the ventricle and in the aorta, and to decrease markedly the total integrated pressure developed during systole in dogs.

The electronic system controlling the unit is triggered by the QRS complex of the electrocardiographic signal. An arbitrary adjustment of the pump is made so that hydraulic events are synchronous, thus decreasing intraventricular ejection pressure and heart work (Fig. 9).

This technique differs in principle from the methods employing a pump-oxygenator. In the method reported here only the arterial system is cannulated. All the blood circulated passes through the heart and lungs of the subject.

The rapid change of direction in which blood flows through tubes of varying sizes suggests extremes of pressures and significant turbulence. The design of the ventricle and tapered tubing, the low hemolysis observed, and the resonance of the pulse waves noted in the pressure tracings indicate less blood trauma than we had anticipated. In the nonbiologic system, one-half hour of perfusion of dog blood at a rate of 4,000 ml. per minute through a 16 Fr. catheter resulted in a 50 mg. per cent increase in a plasma hemoglobin concentration.

Improper timing may cause mammalian spontaneous and mechanical hydraulic events to be superimposed, with systolic pressure and cardiac work increasing (Fig. 10). Continuous monitoring permits ready adjustment of the timing of specific phases of pump action (delay, inject, aspirate) so that pump aspiration coincides with heart systolic ejection to achieve the desired result.

The ideal clinical situation to which the use of this apparatus and method is adapted would appear to be that involving acute heart failure in hypertensive cardiovascular disease, myocardial infarction, or short duration circulatory

assistance to render a patient's condition suitable for definitive surgical intervention. It is probable that acute cardiac decompensation secondary to other causes may respond favorably.

APPENDIX

Detailed Description of the Apparatus.—The actuator consists of a Plexiglas receptacle to hold the ventricles. An integral part of this receptacle is a cylinder in which a piston provided with Bellofram seals operates (Fig. 2). The front part of the cylinder is in continuity with the receptacle and contains the actuating liquid (water or saline). A Bellofram seals the liquid in the chamber while giving minimum friction and wear. As the piston is moved back and forth, the liquid in this chamber is transferred from the cylinder into the receptacle, compressing the ventricle. As the piston withdraws, the liquid is drawn into the cylinder from the receptacle and pulls the ventricle back to its initial open position. There is no reliance upon resilience of the ventricle to regain original volume. Compressed air moves the piston forward. A spring is provided to effect the return stroke. Thus, this is a proportioning pump with a stroke volume independent of back pressure. Filling the receptacle and cylinder with liquid, displacing all air, obligates displacement of a predetermined quantity of blood in the exact quantity, stroke after stroke.

The actuator therefore is pneumatically operated, although the ventricle is hydraulically operated. The piston operates between fixed stops, one of which is adjustable by means of the calibration control. As long as the air pressure is sufficient to move the piston between the stops, the displacement of the pump will be the same, regardless of back pressure. The return spring is housed in a tube which also provides bearing surfaces for the piston. On the outside of this tube, calibration is provided so that the stroke adjustment may be accurately controlled and readily changed by means of a handwheel.

The actuator readily attaches to the cabinet of the electronic power supply (Fig. 5). There is no electrical connection between the power supply and the actuator, but a small plastic air hose, ¼ inch outside diameter, delivers compressed air to the actuator.

A pressure gauge and an air regulator are incorporated into the power supply. The case for this measures 9 by 10 by 18 inches. The output from the regulator is directed to a solenoid valve, and the solenoid's output is taken to the actuator. Air pressure required is of the order of 60 p.s.i. when fast action of the actuator is desired. By controlling the air pressure the magnitude of the "systolic stroke" pressure of the unit may be controlled (during the diastole of the heart).

The electronic power supply serves two purposes. One is to provide a controllable variable pulse rate for the actuator when it is used as a pump. The other is to provide a synchronizable control for the actuator. Fig. 4 is a block diagram indicating the major components in the electronic actuator or power supply. One block is the power supply which converts the AC to the DC voltage suitable for the amplifiers and trigger circuits. A second block is a single-ended amplifier with the input controllable so that the amplitude of the synchronizing pulse, that is the QRS part of the signal, may be adjusted. The next part of the electronic power supply is the time-delay network in the output and a gas tube trigger. This portion of the circuit provides a delayed synchronous pulse for another E-J circuit, again modified so that, once tripped, the trigger circuit remains in the tripped condition for a controlled length of time. The output of this circuit is fed to a buffer amplifier which in turn triggers a thyratron, which in turn controls the solenoid valve. The time delay network is controllable from about 0.05 to 0.6 sec. Systolic time is controllable from 0.15 to 0.6 sec. With this electronic power supply it is therefore possible to take a predetermined hydraulic pulse pattern and superimpose it on the aorta, phased in any desired manner with the systole. By controlling the air pressure, the magnitude of the systole of the unit (the diastole of the patient) may be controlled.

One ventricle is capable of establishing a flow of up to 5,000 ml. per minute against the pressure heads of narrow catheter orifice and mean arterial pressure. The flow rate from the pump is controlled in two ways, by the displacement per stroke and by the stroke rate. The latter can be varied from 5 to more than 100 pulses per minute.

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PULMONARY AND BRONCHIAL CIRCULATION IN CHRONIC LUNG APNEUMATOSIS

Physiologic and Anatomic Studies in a Case of Traumatic Rupture of the Main-Stem Bronchus Treated by Pneumonectomy

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RUPTURE of a main bronchus is now considered a relatively common complication of severe trauma to the chest. This condition was first described, from the anatomic point of view, more than fifty years ago.[1] Since 1939,[5] the clinical picture has been more frequently recognized during life,[16] resulting in pulmonary resections, and restoration of bronchial continuity, sometimes many years after injury.[2, 3, 4, 6, 8, 9, 10, 12, 13, 14] However, few data are available regarding changes in pulmonary circulation in such cases of long-term nonventilated lungs. Santy and co-workers[12] reported a patient with high oxygen content in the corresponding pulmonary branch. Troemé and Chedal[15] recorded the inversion of pulmonary flow in a case of chronic lung apneumatosis. The connections between the pulmonary circulation and the systemic circulation has been the subject of many clinical and experimental investigations.[7, 11, 17]

In this paper we shall emphasize the clinical, physiologic, and anatomic findings obtained in a case of traumatic chronic apneumatosis studied 14 years after injury.

CASE REPORT

(I. C. T. No. 28.673.) A 19-year-old white girl, at the age of 4, was knocked down by a horse, suffering a closed injury of the left hemithorax. She was admitted to a hospital severely incapacitated. From familial reports, she exhibited symptoms of dyspnea, cough, subcutaneous emphysema, and cyanosis. She was discharged to her home clinically improved about 3 months later. The patient has been asymptomatic up to the present, except for several episodes of bronchitis. Chest roentgenograms taken in 1959 disclosed an opacity of the whole left hemithorax. For this reason she was admitted to the Instituto de Cirugía Torácica in March, 1959.

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Physical examination revealed absent breath sounds over the entire left hemithorax. The apical cardiac impulse was shifted to the left. No murmurs were audible. Blood pressure was 110/70 mm. Hg. Routine laboratory studies were normal. Chest roentgenograms revealed a shift of the trachea and mediastinum to the left and a homogeneous density throughout the left hemithorax (Fig. 1). A bronchogram showed that the left main-stem bronchus ended blindly, approximately 3 cm. distal to the carina (Fig. 2).

The electrocardiogram disclosed unusual axis deviations, but was reported as normal.

Basic pulmonary function studies showed a proportional diminution of vital capacity and maximum breathing capacity. Arterial oxygen saturation was normal (Table I).

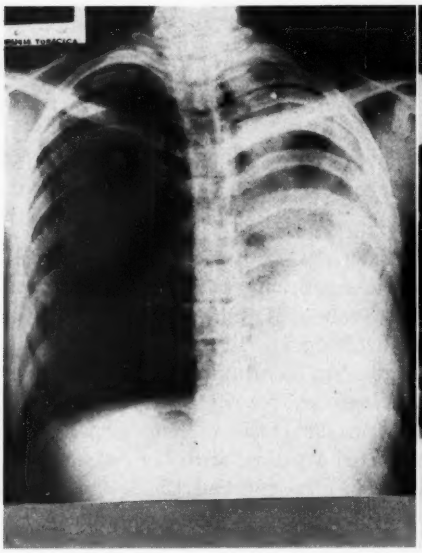

Fig. 1.

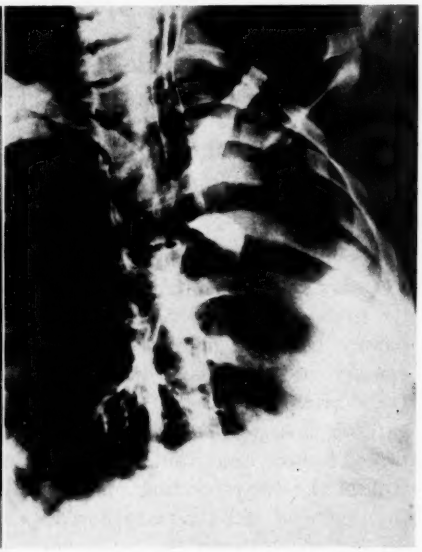

Fig. 2.

Fig. 1.—Roentgenogram of the chest showing the opacity of the whole left hemithorax and a shift of the mediastinum to the left.

Fig. 2.—A bronchogram revealed that the left main-stem bronchus ended blindly. Right lung has a normal bronchial pattern.

TABLE I. BASIC PULMONARY FUNCTION STUDIES

Tidal volume—480 c.c.
Respiratory frequency—19 breaths per minute
Respiratory minute volume—5.9 L./M.^{2}/min.
Vital capacity—1,950 c.c. (62 % of predicted normal)
Maximum breathing capacity—35 L./min. (56 % of predicted normal)
Air velocity index—0.90
Breathing reserve index—74 %
Arterial blood oxygen saturation—97 %

During right heart catheterization, pressure records from the right atrium, right ventricle, the main pulmonary artery, and right and left stems were normal except for the left pulmonary branch in which in the "wedge" position a mean pressure approximately three times higher than that in the trunk was recorded (Table II).

Blood samples from all these sites and also from the brachial artery were obtained. Oxygen and carbon dioxide determinations were performed according to Van Slyke manometric technique. In the left pulmonary artery, oxygen saturation of 96 per cent was found;

in the right stem there was an oxygen content 2 volumes per cent higher than that in the right ventricle (Table III).

Cardiac output was calculated by the Fick principle. Systemic output was determined by considering the oxygen arterial-venous difference between the arterial sample and that from the right ventricle. Pulmonary output was calculated by considering the arterial-venous difference between the arterial sample and that from the right pulmonary artery. In this way, a left-to-right shunt in the pulmonary circuit was evaluated. Total pulmonary resistance and right ventricle work were also calculated (Table IV).

Fig. 3.

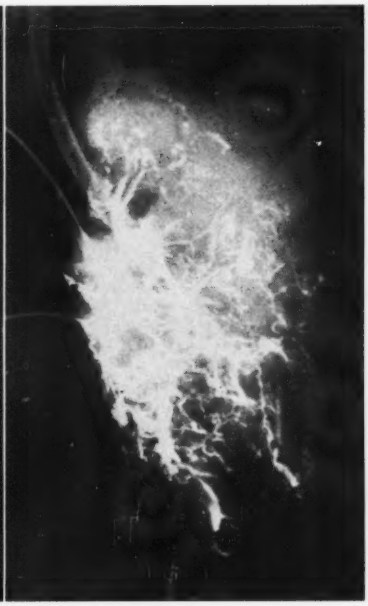

Fig. 4.

Fig. 3.—Gross specimen of the left lung with injection of bronchial tree which shows confluent bronchiectasis that replaces most of the pulmonary tissue.

Fig. 4.—Gross specimen of the left lung with injection of bronchial arteries which reveals their overdevelopment.

TABLE II. PRESSURES OBTAINED IN CARDIAC CATHETERIZATION*

Right atrium	3/–2	(0)
Right ventricle	25/2	
Right pulmonary	23/12	(17)
Left pulmonary	60/40	(50)

*All pressures in millimeters of mercury. Figures in parentheses indicate mean pressures.

TABLE III. DETERMINATION OF OXYGEN CONTENT (VOL. %) AND SATURATION

Right atrium	13	(67 % sat.)
Right ventricle	13	(67 % sat.)
Right pulmonary	15	(77 % sat.)
Left pulmonary	18.60	(96 % sat.)
Brachial artery	18.75	(97 % sat.)

Arterial blood oxygen capacity—19.33 vol. %

TABLE IV. DATA OBTAINED IN CARDIAC CATHETERIZATION

Oxygen consumption—270 c.c./min.
Systemic A-V O_2 difference—5.75 vol. %
Pulmonary A-V O_2 difference—3.75 vol. %
Systemic output—4.8 L./min.
Pulmonary output—7.2 L./min.
Left-to-right shunt—2.4 L./min.
Total pulmonary resistance—190 dynes sec. cm.$^{-5}$
Right ventricle work—0.98 Kg. M/min./M.^{2}

On May 1, 1959, a left posterolateral thoracotomy was carried out. A small left lung measuring 15 cm. by 12 cm., adherent to vertebral gutter, was found. The pleural cavity was free on the anterior side. The other sides were freed with difficulty because of adhesions to the parietal surface, including a great number of systemic vessels. Two enlarged bronchial arteries, 2 mm. in diameter, coming directly from the aorta were found. The left lung appeared completely covered by a thick fibrous coat which prevented its distention. The left

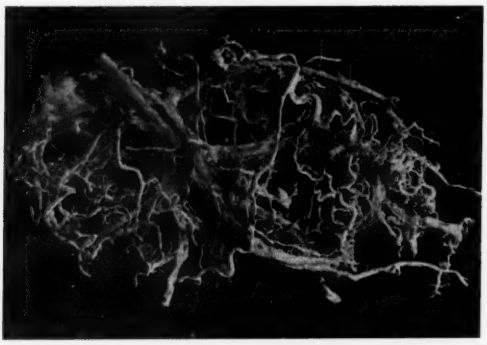

Fig. 5.—Case from the resected lung by injection of pulmonary and bronchial systems demonstrates bronchial arteries as vermiform vessels and large anastomosis between the two systems.

main-stem bronchus revealed a scarred stricture 3 cm. distal to the carina. The left pulmonary artery was enlarged. The pulmonary veins were of reduced diameter and were actually transformed into fibrous cords. Left pneumonectomy was performed. The postoperative course was uneventful. Right heart catheterization was performed again one month later and revealed no abnormalities (Table V).

TABLE V. POSTOPERATIVE CARDIAC CATHETERIZATION

	PRESSURES (MM. Hg)	O_2 CONTENT (VOL. %)
Right atrium	3/ 0 (1)	15.50
Right ventricle	20/ 2	15.87
Right pulmonary	18/ 8 (12)	15.68
Brachial artery	120/75 (95)	20.30
Arterial O_2 capacity—21 vol. %		

Gross specimen of the left lung showed that most pulmonary tissue was destroyed and replaced by confluent bronchiectasis (Fig. 3). Injection of opaque substance through bronchial arteries revealed their overdevelopment (Fig. 4). The cast obtained by injection of the pulmonary and bronchial vessels demonstrated a great number of anastomoses between the two systems (Fig. 5).

DISCUSSION

Although we have no reliable information on the trauma that occurred in childhood to this patient, it was undoubtedly serious and caused the rupture of the bronchus which was revealed 14 years later. At first, bronchial occlusion was probably incomplete and repeated infections in the pulmonary tissue distal to the injury occurred, causing bronchial suppuration and pneumonitis with resultant lung destruction. However, the patient had not suffered from any evident symptoms.

The lung function tests showed the usual findings in restrictive pulmonary insufficiency. Oxygen saturation in arterial blood was normal. The most striking features were found in right heart catheterization. Pressure values of the right atrium and ventricle, main pulmonary artery and right main stem were normal. Nevertheless, when the catheter was introduced into the left pulmonary artery ("wedge" position), pressure was three times higher than that from the trunk or right branch. Likewise, oxygen content at this site was approximately the same as that of arterial blood. On the other hand, in the right pulmonary artery we demonstrated a higher oxygen content (2 volumes per cent) than in the right ventricle. Consequently, we postulated a left-to-right shunt from systemic circuit to right pulmonary artery, due to an overdevelopment of the systemic arteries and their anastomosis with the pulmonary circuit causing an inversion of blood flow in the left lung. This effect of the bronchial system on the pulmonary circuit, as has already been pointed out by other authors,[7] would be an important factor regulating the perfusion-ventilation ratio in such cases of long-term nonventilated lungs. That effect, producing back pressure, prevents blood flow through nonventilated areas and consequently avoids anoxemia.

In our case, it was decided to perform pneumonectomy not only because of the lung destruction and infection, but also for a hemodynamic reason, that is, the burden on the left side of the heart and the increase of pulmonary flow (limited to the right lung) caused by blood shunting from the systemic circuit, estimated to be 2.4 L. per minute.

SUMMARY

A case of traumatic rupture of the left main-stem bronchus, secondary to closed trauma that occurred 14 years previously, is described. Pulmonary function tests done before and after operation showed common alterations in restrictive pulmonary insufficiency, but without anoxemia.

Right heart catheterization was performed before and after operation.

A left-to-right shunt from bronchial arteries to pulmonary circuit was demonstrated. After pneumonectomy, no alterations in pulmonary circulation were found.

Pneumonectomy was performed because of lung destruction and to avoid a left-to-right shunt in the pulmonary vascular bed reduced to one half.

Pneumonectomy appears mandatory in such cases.

Gross specimen of the left lung demonstrated the abnormal development of the lung collateral circulation and its anastomosis with the pulmonary system.

The authors gratefully acknowledge the technical assistance of Mrs. Nelida P. de Lora.

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RECONSTRUCTION OF THE RAW SURFACE AFTER PULMONARY SEGMENTAL RESECTION

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A CONSIDERABLE number of pulmonary segmental resections have been performed since Churchill first described the operation in 1939. Lesions confined to a given bronchopulmonary segment are frequently treated by pulmonary segmental resection. Because of the advent of antimicrobial therapy, transgression of diseased tissue is less a problem today than in the past. Chamberlain and others have shown that in the majority of lobectomies for tuberculosis, diseased tissue is traversed and a true fissural separation between lobes is not always present.[1] Thus, it seems the factor of dissemination is probably no greater in the well-chosen segmental resection than in the lobectomy where fissures are incomplete.

A problem remains in the treatment of the raw surface following segmental resection. Many outstanding surgeons advocate leaving the raw edges open. Chamberlain[2] states the denuded area should not be closed or covered with a pleural graft. He believes any attempt to close the raw surface would only distort the segment, interfere with its ability to breathe, and the sutures would probably cut out in the early postoperative period during breathing or coughing. Blades uses parietal pleura to close the raw surface. Overholt leaves the denuded area open. Samson[4] and his associates suture most of the raw edges following segmental resection.

A number of essential questions may be asked concerning the problem of the different methods of treating the raw surfaces:

1. Does closing the raw edges cause abscess formation within the closed space?

2. Does closing the raw edges reduce pulmonary function?

3. Does closing the raw edges increase or decrease the incidence of empyema or broncho-pleural fistula?

4. Does closing the raw edges increase or decrease prolonged air leakage?

Attempted answers to these pertinent questions are the subject of the present report.

MATERIAL AND METHOD

One hundred and ten pulmonary resections from the Veterans Administration Hospital, Albuquerque, New Mexico, have been analyzed. In 66 cases (60 per

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cent) the denuded areas were coapted, and in 44 (40 per cent) the raw edges were not coapted. One hundred and eight patients were male and 2 were female. Approximately 95 per cent of the patients had multiple segments removed. Ninety-seven patients were operated upon for tuberculosis, 2 for lung abscess, 2 for coccidioidomycosis, 2 for bullous emphysema, and 7 for bronchiectasis. Diseased segments were determined preoperatively by detailed evaluation, frequently including tomography and bronchography. All patients were bronchoscoped preoperatively.

The posterolateral chest wall incision is used routinely, and the intercostal incision is used for entering the pleural space. The segmental resection is performed using the individual ligation technique of artery, bronchus, and segmental vein as described by Childs and Nelson.[3] Following control of hemorrhage and air leaks in the denuded area, the edges are apposed with a running 3-0 chromic suture on an atraumatic needle. Suturing is accomplished with the segment inflated and great care is taken to prevent tension or torsion on the bronchus. The closed area manifests few or no air leaks (Figs. 1-6).

RESULTS

In contrasting the reconstructed cases with the nonreconstructed cases, the following statements may be made:

1. No evidence of abscess formation occurred within the sutured edges. In many closed cases a collection of fluid developed between the coapted edges; this did not interfere with segment re-expansion, and, as stated before, did not predispose to abscess formation. Chest roentgenograms taken during the immediate postoperative period, and 2 or 3 months after resection, did not show any conclusive evidence of abscess formation within the enclosed space. The fluid collection within the enclosed space completely resolved in most cases between 8 and 10 weeks postoperatively. The temperature curve was flat and leukocytic response was normal during the period of fluid resolution (Figs. 7, 8, 9).

2. The over-all incidence of bronchopleural fistula was 6.4 per cent for the 110 cases, 4.5 per cent in the 66 cases of reconstruction and 9.1 per cent in the 44 nonreconstructed cases. Thus, the incidence of bronchopleural fistula in the reconstructed cases was one half the incidence in the nonreconstructed cases.

3. The incidence of empyema was identical; 4.5 per cent in the reconstructed cases and 4.5 per cent in the nonreconstructed groups.

4. Atelectasis requiring bronchoscopy for correction occurred in 6 cases; 3 (4.5 per cent) occurred in the reconstructed group and 3 (6.8 per cent) in the nonreconstructed group.

5. The average number of days to elapse before the removal of the anterior and posterior chest tubes was the same in both series, namely 4.1 days.

6. Prolonged air leaks occurred in 3 per cent of the coapted series and 6.8 per cent of the noncoapted series.

7. Thorough scrutiny of temperature chart, hematological picture, postoperative chest roentgenograms, progress notes of doctor and nurse revealed no increased morbidity in the patients in whom raw edges had been coapted.

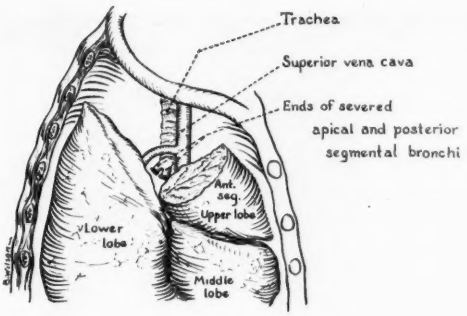

Fig. 1.

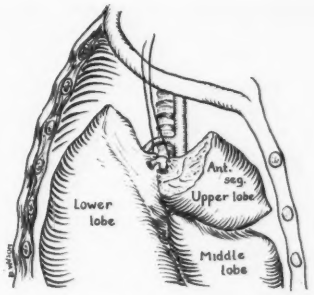

Fig. 2.

Fig. 1.—Denuded surface following apical and posterior segmental resections of the right upper lobe.

Fig. 2.—Beginning of reconstruction of the denuded surface shown in Fig. 1.

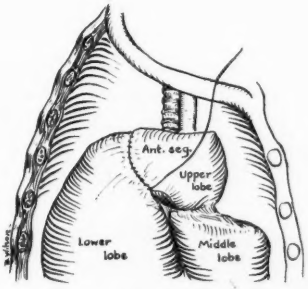

Fig. 3.

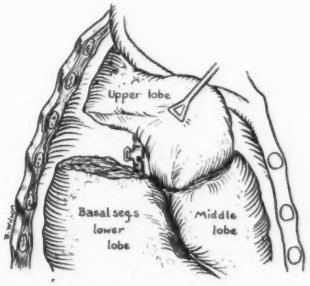

Fig. 4.

Fig. 3.—Completion of the reconstruction.

Fig. 4.—Resected superior segment of the right lower lobe.

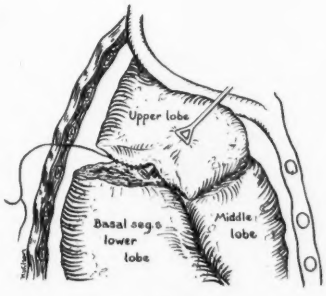

Fig. 5.

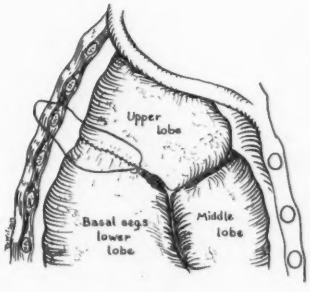

Fig. 6.

Fig. 5.—Beginning reconstruction, posteriorly, of the denuded surface shown in Fig. 4.

Fig. 6.—Anterior continuation of reconstruction shown in Fig. 5, and the completed reconstruction.

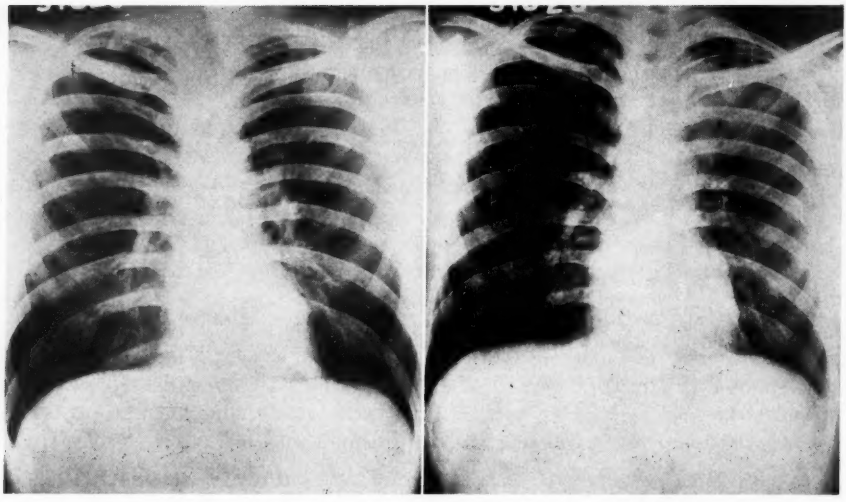

Fig. 7. Fig. 8.

Fig. 7.—Preoperative posteroanterior chest x-ray made April 4, 1954, which shows a lesion in the left second interspace.

Fig. 8.—Postoperative posteroanterior x-ray of chest made April 12, 1954. Lesion (Fig. 7) removed and a collection of fluid observed in the left second interspace.

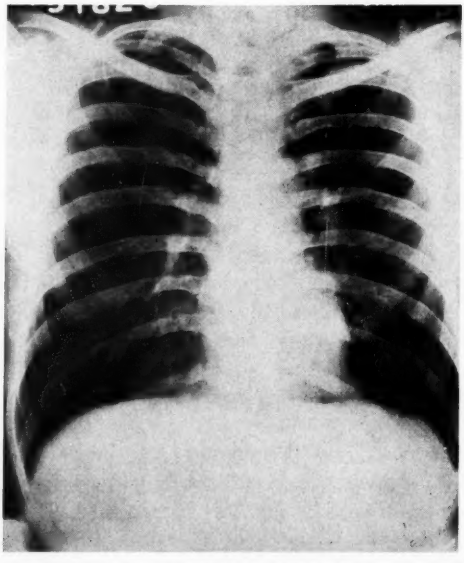

Fig. 9.—Posteroanterior x-ray made June 7, 1954, which shows resolution of the fluid collection in the left second interspace seen on April 12, 1954 (Fig. 8).

The comparative complications of both the reconstructive and nonreconstructive series are listed in Table I. Reference to this table readily shows no inherent risk in the reconstructive method, but rather an apparent advantage in that the usual complications associated with resectional therapy are reduced.

TABLE I. COMPLICATIONS OCCURRING IN NONRECONSTRUCTED AND RECONSTRUCTED CASES FOLLOWING SEGMENTAL RESECTIONS

COMPLICATIONS	RECONSTRUCTED (66 CASES)	NONRECONSTRUCTED) (44 CASES)
Pneumothorax	2 (3%)	2 (4.5%)
Atelectasis	3 (4.5%)	3 (6.8%)
Empyema	3 (4.5%)	2 (4.5%)
Bronchopleural fistula	3 (4.5%)	4 (9.1%)
Prolonged air leaks	2 (3%)	3 (6.8%)

Preoperative and postoperative pulmonary function studies were performed on 30 of these patients by Dr. A. N. Longfield, Chief of the Cardiopulmonary Laboratory at the Veterans Administration Hospital, Albuquerque, New Mexico. Twenty-one patients were in the reconstructed group and 9 in the nonreconstructed group. He was unable to demonstrate more loss of pulmonary function in the reconstructed group than in the nonreconstructed group. Table II shows the comparative pulmonary function studies of the reconstructed and nonreconstructed series.

Table II shows that in the 9 patients in whom there was no reconstruction of raw edges, a comparison of preoperative and postoperative MBC (maximum breathing capacity) showed an average loss of 18.9 L.

In 21 patients who had the raw edges reconstructed, a comparison of the preoperative and the postoperative MBC showed an average loss of 4.9 L.

There is a wide variation in the maximum breathing capacity in the patients within each group, so that the average loss of function in these two groups is probably not highly significant. However, it is probable that the patients with reconstruction do not lose more pulmonary function than those with no reconstruction.

DISCUSSION

Segmental resection is a frequently used procedure, but the problem of handling the remaining raw area has not been standardized.

Samson reported an incidence of empyema of 23 per cent in thirty segmental resections when the lung surfaces remained raw; this he considered excessive and subsequently he began closing most of the raw surfaces. The empyema rate declined from 23 to 5 per cent in 40 cases using a suture closure technique of the raw edges.[4] The incidence of empyema in our groups was 4.5 per cent. Samson states that there is minimal, if any, diminution in breathing capacity if the closure is performed with the lobe partially expanded and without torsion on the bronchus.

It is quite obvious that other factors may be responsible for postoperative complications; however, simple closure of the raw edges does not cause increased complications.

TABLE II. RESULTS OF PREOPERATIVE AND POSTOPERATIVE PULMONARY FUNCTION STUDIES IN SEGMENTAL RESECTION CASES (IN CHRONOLOGICAL ORDER)

DIAGNOSIS	RECONSTRUCTED (REGISTER NO.)	NONRECONSTRUCTED (REGISTER NO.)	SEGMENT REMOVED	MAXIMUM BREATHING CAPACITY PREOP.	MAXIMUM BREATHING CAPACITY POSTOP.	LOSS OF MBC POSTOP.
TBC	46781		Apical and posterior sub. anterior RU lobe	119	126	None
TBC	60430		Wedge apical LU lobe	222	186	36
TBC	62419		Apical posterior LU lobe	154	171	None
TBC	53547		Apical posterior LU lobe	178	183	None
TBC		57136	Decortication apical posterior LU lobe, 3-rib thoracoplasty	131	126	5
TBC		60729	Apical posterior LU lobe	168	157	11
TBC	57246 (female)		Apical posterior RU lobe	60	64	None
TBC	60420		Wedge apical posterior LU lobe	162	175	None
TBC	57335		Apical posterior LU lobe	136	109	27
TBC	61089		Apical posterior LU lobe	162	171	None
TBC	44731		Apical posterior anterior LU lobe	98	106	None
TBC	60220		Apical and posterior wedge, anterior RU lobe	101	115	None
TBC	61269		Apical posterior LU lobe	173	166	7
Bronchiectasis	47938 (female)		Wedge apical posterior LU lobe, lingualectomy basilar LL lobe	87	96	None
TBC		57687	Apical posterior LU lobe	158	110	48
TBC	61356		Apical posterior and anterior LU lobe	44	65, 5 mo. 79, 9 mo.	None
TBC		49676	Apical posterior LU lobe, thoracoplasty	139	146	None
TBC		61556	Apical posterior RU lobe, decortication	188	178	10
TBC	45096		RU lobe lobectomy, lateral segment RM lobe	124	96	28
TBC	59777		Apical posterior RU lobe	165	136	29
TBC	48346		RU lobe, wedge superior RL lobe	153	143	10
TBC	43793		RU lobe, superior RL lobe, 3-rib thorocoplasty	142	92	50

TABLE II—CONT'D

DIAGNOSIS	RECONSTRUCTED (REGISTER NO.)	NON-RECONSTRUCTED (REGISTER NO.)	SEGMENT REMOVED	MAXIMUM BREATHING CAPACITY PREOP.	MAXIMUM BREATHING CAPACITY POSTOP.	LOSS OF MBC POSTOP.
Lung abscess		61654	Superior LL lobe	113	140	None
TBC		59565	Apical posterior and anterior LU lobe	158	92	66
Bronchiectasis		45490	Basilar segment LL lobe	156	111	45
TBC	60311		Apical posterior LU lobe	119	135	None
TBC	60750		Superior LL lobe	166	172	None
Bronchiectasis	62193		Basilar RL lobe	115	114	1
TBC		49569	Apical posterior LU lobe	128	109	19
TBC	50523		Apical, sub. posterior LU lobe Bleb superior LU lobe	159	154	5

The simplicity of the suture method, the negligible additional surgical and anesthetic stress, plus the fact that the technique can be performed in 5 to 10 minutes, make the closing of raw surfaces of resected lung after segmental resection a safe procedure. It is the belief of the authors that in cases of reconstruction the postoperative course has been smoother. Certainly the incidence of prolonged air leaks and bronchopleural fistula has been reduced.

CONCLUSION AND SUMMARY

1. A simple technique for closing the raw surface remaining after segmental resection has been discussed.

2. X-ray studies and pulmonary function studies were presented to show that no detrimental effects are inherent to the method per se; no alteration in pulmonary function or abscess formation was demonstrable.

3. Reconstruction was done in 66 cases out of one hundred and ten segmental resections and the results to date indicate the technique is of merit.

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SEGMENTAL RESECTION OF THE BRONCHUS WITH THE AID OF PREOPERATIVE SUBMUCOSAL BIOPSY

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SEGMENTAL RESECTION of a bronchus has been mainly confined to the resection of adenomas or of strictures of the bronchi. There is the occasional case, however, in which a malignancy is present in a position where an ordinary lobectomy would not remove the entire tumor. Yet, in some of these cases, lobectomy is mandatory because of the patient's reduced cardiopulmonary reserve. A lobectomy plus a segmental resection of the adjoining main bronchus and final reconstitution of the respiratory passages by bronchial or tracheobronchial anastomosis would solve the problem. It would be essential, however, to know whether the anastomotic site is clear of tumor before the procedure is begun. This could be accomplished preoperatively by deep submucosal bronchial biopsies of the potential sites of anastomosis, via the bronchoscope, or at the time of surgery by frozen section of these sites. It is with the above in mind that we should like to present a case of carcinoma of the lung in which the procedures outlined were successfully accomplished. We know of no other case in the literature that has followed this particular technique.

Although pneumonectomy or lobectomy is the procedure of choice in the treatment of carcinoma of the lung because of removal of the associated lymphatic fields, there are a definite number of patients with this disease in whom such a formidable procedure would so embarrass their already diminished cardiopulmonary reserve as either to be severely crippling or to even lead to death. In such a group of patients we feel that segmental resection of the bronchus preceded by deep submucosal bronchial biopsies would allow these patients to receive adequate surgical therapy of their lesions. Previously these cases were considered to be inoperable because of the coexisting problems of the strategic location of the tumor combined with the need for preservation of as much functional lung parenchyma as possible. As is apparent from the age incidence of carcinoma of the lung, it is in just these age groups that cardiopulmonary problems become manifest.

Although other authors have reported successful experiences with segmental resection for carcinoma, in small series, the largest published series of such cases

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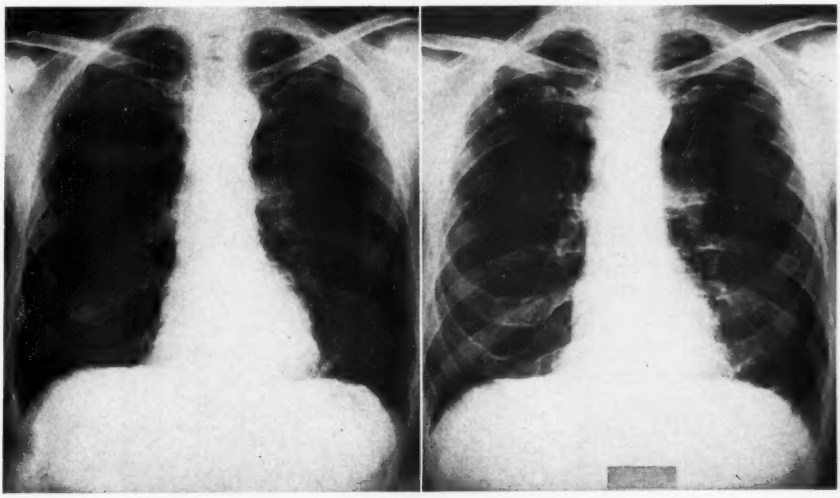
to date is that of Johnston and Jones.[7] In a series of 98 patients operated upon between 1953 and 1958 these authors report an 80 per cent 1-year survival and an 8 per cent mortality rate with segmental resection as compared with a 74 per cent 1-year survival and a 9 per cent mortality rate for lobectomy with carcinoma of the bronchus. The conclusions of this paper are threefold: (1) segmental resection is a reasonably safe operation, (2) the early follow-up statistics are no worse than those of lobectomy, and (3) surgery can now be offered to a greater number of patients with bronchial carcinoma.



A. *B.*

Fig. 1.—A roentgenogram of the chest made in 1958 *(A)* which shows prominent left hilum unchanged from previous film *(B)* which was taken in 1955.

CASE REPORT

Patient J. L., a 64-year-old man, was admitted to The Mount Sinai Hospital for the fourth time on May 12, 1958, with a chief complaint of hemoptysis of 5 days' duration. Roentgenograms of the chest showed a prominent left hilum (Fig. 1, *A*) which was little different from an x-ray study in 1955 (Fig. 1, *B*).

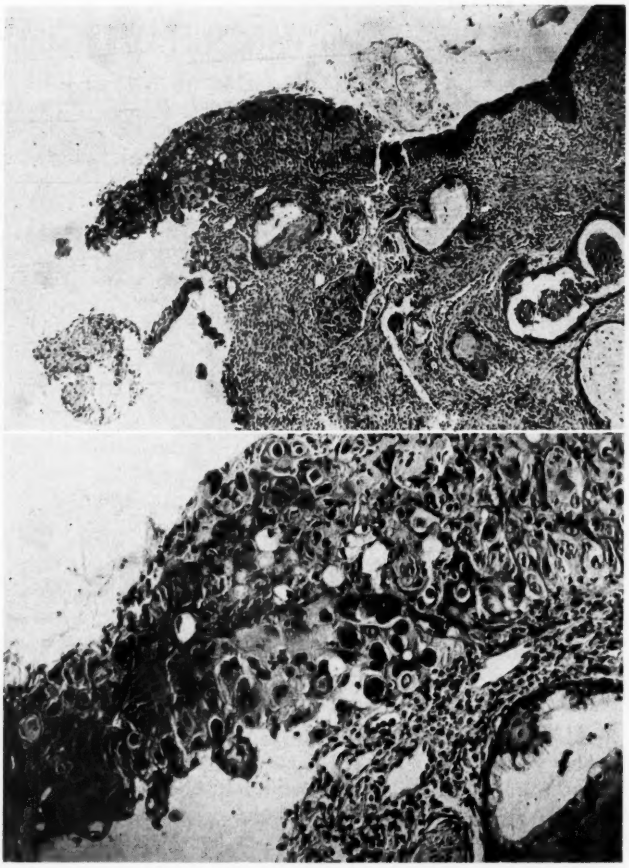
Bronchoscopy revealed a thickening of the upper lip of the left upper lobe orifice. The mucosa in this area bled easily but no area of active bleeding and no mass lesion was visualized. Biopsy of the thickened left upper lobe spur was reported as showing an infiltrating squamous cell carcinoma (Fig. 2, *A* and *B*). In view of this report the patient was bronchoscoped a second time in order to determine whether he was a candidate for segmental resection. It was, therefore, requested that biopsies be taken from the left upper lobe orifice, the left tracheobronchial angle (Fig. 3), and 1 cm. below the left upper lobe orifice with adequate deep submucosal bites to determine spread. These biopsies were all negative with the exception of that of the left upper lobe orifice, which confirmed the original report.

On June 6, 1958, through a left intercostal incision, a left upper lobectomy with segmental resection of the left main bronchus was performed. A frozen section of the specimen of main bronchus showed carcinoma extending submucosally to the proximal line of resection

(Fig. 4, *A* and *B*). Repeat cuffs of the left main bronchus were resected proximally until two successive cuffs were negative for carcinoma. An end-to-end anastomosis of the proximal and distal ends of the main bronchus was then performed at a point 0.5 cm. from the carina.

Paraffin sections of the specimen were reported as showing superficial infiltrating squamous cell carcinoma involving the left upper lobe bronchus and the left main bronchus.

A.



B.

Fig. 2.—*A*, Low-power view of bronchoscopic biopsy of thickened left upper lobe spur which shows infiltrating squamous cell carcinoma. *B*, High-power view of Fig. 2, *A*.

Postoperatively, the patient developed a few episodes of atrial arrhythmia but otherwise the course was unremarkable and the patient was discharged on the thirteenth postoperative day.

Bronchoscopy performed 11 months postoperatively showed no evidence of recurrent disease. The anastomosis was intact and well healed with no stenosis.

Aside from a pneumonia occurring 17 months postoperatively, that cleared promptly under therapy, and a moderate postnasal drip the patient has been asymptomatic. Roentgenograms of the chest made 20 months after operation (Fig. 5) showed no evidence of recurrent disease.

DISCUSSION

The tumor in this case presented only as a thickening of the upper spur of the left upper lobe orifice. The tendency of bronchogenic carcinoma to spread proximally in submucosal lymphatics without any concurrent gross evidence of spread is well known.[8, 9, 10] Also well known is the fact that some of the most rapidly spreading bronchogenic carcinomas are evidenced bronchoscopically only

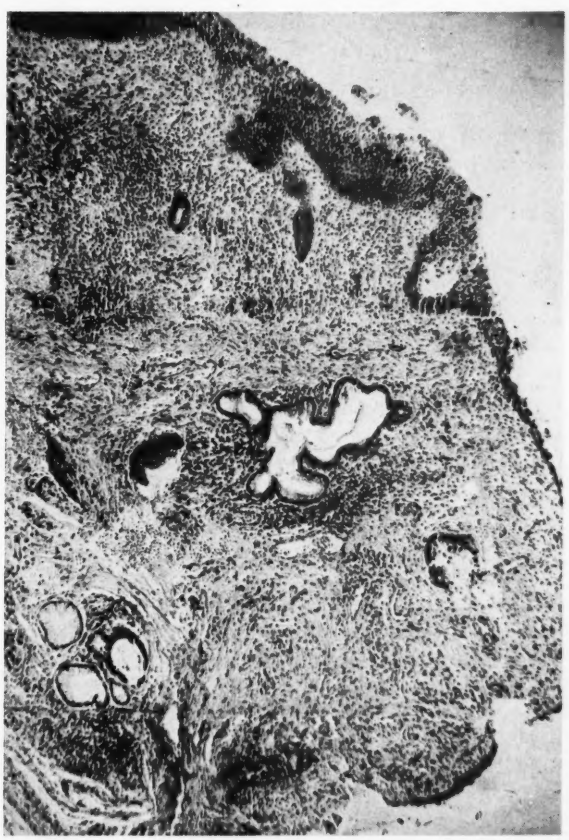


Fig. 3.—Bronchoscopic submucosal biopsy of left tracheobronchial angle which shows absence of carcinoma.

as a thickening or granularity of the mucous membrane without the presence of an endobronchial mass. Superficial biopsy gives no idea of the condition of lymphatics. In pneumonectomy the bronchial stump recurrence may be due to lymphatic obstruction to begin with. Rabin, Selikoff, and Kramer[11] have shown the value of paracarinal biopsy in detecting such proximal submucosal spread and hence in evaluating the operability of carcinoma of the lung with respect to pneumonectomy.

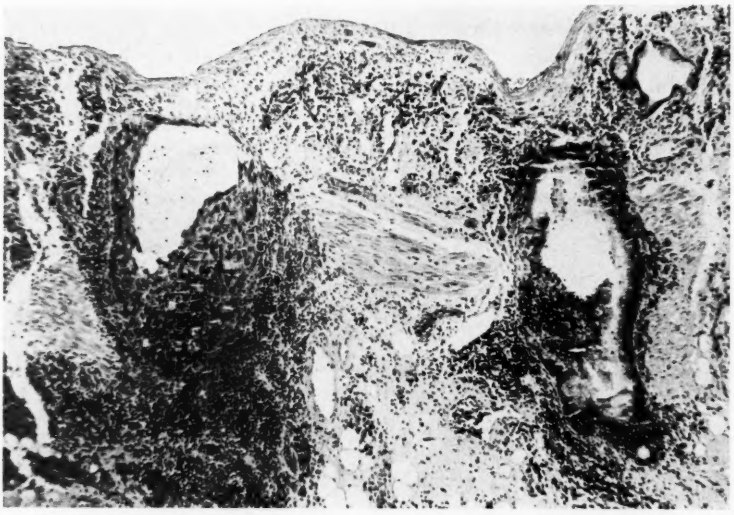


Fig. 4*A*.—Low-power view of proximal edge of surgical specimen of left main bronchus which shows carcinoma in submucosal lymphatics.

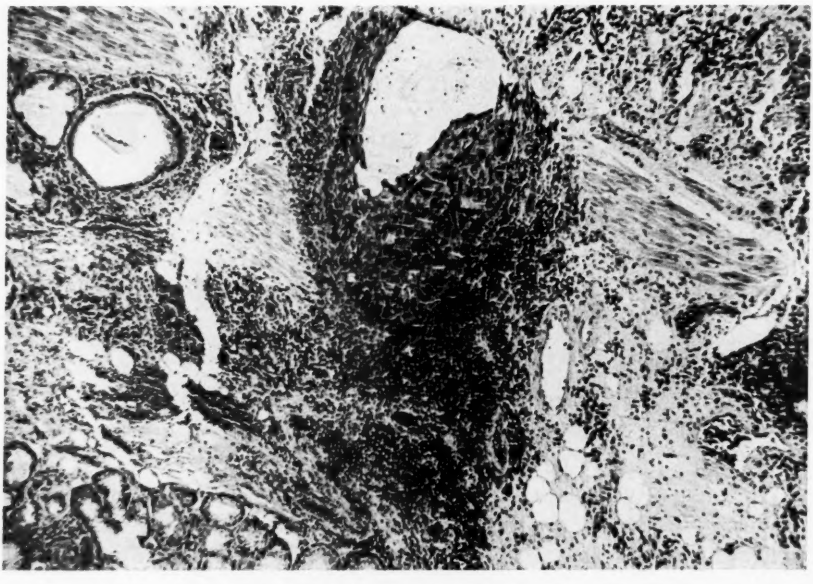


Fig. 4*B*.—High-power view of Fig. 4*A*.

In order to determine the operability of bronchogenic carcinoma with respect to segmental resection, however, the surgeon must be aware of whether or not there are tumor cells at both the proximal and distal lines of resection. In selecting patients with bronchogenic carcinoma suitable for segmental resection, a submucous bronchial biopsy should be performed, via the bronchoscope, at the tracheobronchial angle and 1 cm. below the lower lip of the upper lobe orifice, even though the mucous membrane in these regions appears normal. The tracheobronchial angle is selected for biopsy in preference to the paracarinal area

Fig. 5.—Chest roentgenogram made 20 months postoperatively which shows no disease.

because of the tendency of upper lobe lesions to metastasize to the tracheobronchial angle. If carcinoma is demonstrated in the tracheobronchial angle, these patients are considered inoperable. If this biopsy proves negative and the bronchial biopsy below the upper lobe orifice is positive, a pneumonectomy is indicated. An attempt at segmental resection should be made only if both biopsy specimens are negative.

In our case the preoperative bronchoscopic biopsies at the tracheobronchial angle and 1 cm. below the upper lobe orifice were both negative for carcinoma and, as shown at the time of operation, the tumor extended only to a point 2 cm. from the tracheobronchial angle.

SUMMARY

A case of segmental resection of the main bronchus with lobectomy for bronchogenic carcinoma has been reported. To our knowledge, this case represents the first recorded instance in which preoperative deep submucosal tracheo-

bronchial angle biopsy and biopsy of the bronchial wall distal to the upper lobe orifice were done in order to determine the advisability of performing a segmental resection.

Segmental resection of the bronchus is by now a well-established procedure that can greatly augment the versatility of the surgeon in the treatment of both benign bronchial lesions and malignant endobronchial lesions in which preservation of distal healthy lung tissue is of vital importance.

Tracheobronchial angle biopsy and biopsy of the bronchial wall 1 cm. below the orifice of the upper lobe, to include the submucosa, should be done preoperatively in all cases of contemplated segmental resection for bronchogenic carcinoma involving both the main and the upper lobe bronchus. This should be done in order to rule out the possibility of submucosal lymphatic spread even without gross abnormality of the overlying mucosa. Only if both biopsies are negative should segmental resection be undertaken.

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SIMPLIFIED TREATMENT OF LARGE, SACCIFORM AORTIC ANEURYSMS WITH PATCH GRAFTS

Experiences With 5 Cases

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EXCISIONAL therapy of aortic aneurysms is now well established, but the surgical methods of applying this form of treatment vary, depending upon the nature and location of the lesion.[1] Thus, in sacciform aneurysms with a relatively narrow neck involving only a small part of the aortic circumference, it is possible to employ tangential excision with lateral aortorrhaphy as originally suggested by Tuffier,[2] but only recently applied successfully.[3-6] This consists essentially in isolation of the neck of the aneurysm from surrounding structures and application of an occluding clamp across the base of the neck parallel to the normal aortic wall. With the aneurysm thus isolated from the main aortic channel through which normal circulation is maintained, it is simply excised distal to the occluding clamp and the aortic opening is closed with sutures. This procedure, having the great advantage of simplicity with little or no disturbance of vital circulatory function, may therefore be employed with a relatively low operative risk. Unfortunately, it is not always applicable, since the neck of some sacciform aneurysms may be relatively large with the aneurysmal sac rolled over to incorporate much of the normal aortic wall. In such cases it may be difficult, if not impossible, to apply an occluding clamp across the base of the aneurysm without causing severe constriction or complete occlusion of the aortic lumen. Similarly, repair of such an aneurysm may also cause severe encroachment upon the normal aortic lumen. For these reasons, such sacciform aneurysms may require excision of the involved aortic segments with graft replacement, as must be done for fusiform aneurysms.[1] This procedure, of course, increases the magnitude of the operation, particularly in lesions located in the thoracic and upper abdominal aortic segments, since it imposes the necessity for temporary arrest of aortic circulation and complete replacement of excised aortic segments from which major arterial branches arise. It has been possible to circumvent some of these difficulties and thus reduce the magnitude of the operation by simple excision of the aneurysmal sac

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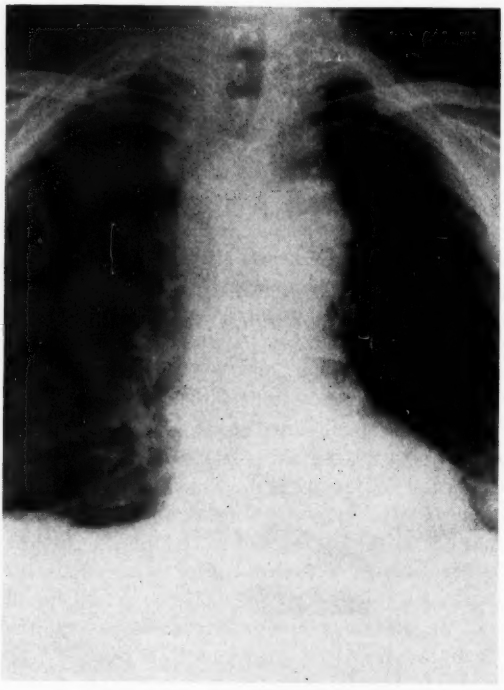

Fig. 1.—Plain roentgenogram of chest in patient described in Case 1, showing upper mediastinal mass displacing trachea to right.

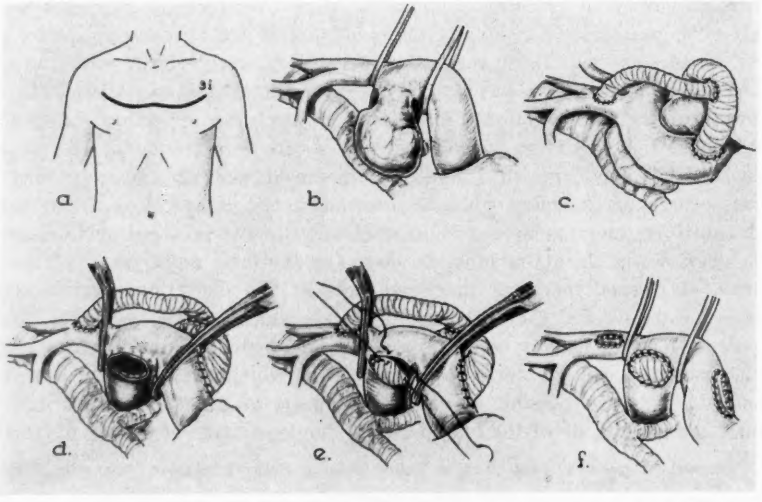

Fig. 2.—Drawing illustrating technical method of local excision and patch graft repair of large sacciform aneurysm arising from posterior wall of aortic arch, shown in Fig. 1.

and lateral aortic repair with a patch graft, as suggested by the early experimental work of Carrel and Guthrie and as previously employed clinically in the treatment of lesions of the abdominal aorta and the major peripheral arteries.[8-10] Indeed, it was the result of this gratifying experience that led us to apply this method in the repair of these extensive forms of sacciform aneurysms of the thoracic and upper abdominal aorta, and the procedure has proved to be so technically satisfactory, as exemplified by the following cases, that we believe it deserves further consideration.

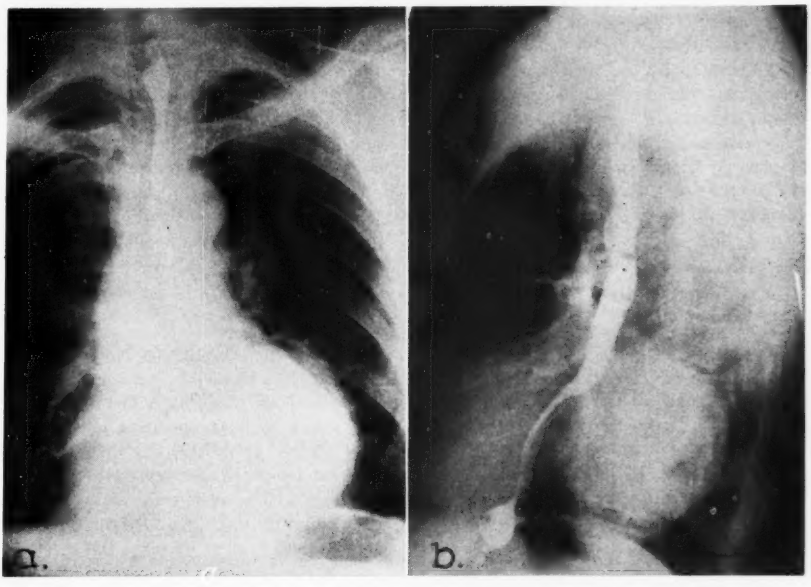

Fig. 3.—*(a)* Posteroanterior and *(b)* left lateral roentgenograms in Case 2 showing sacciform aneurysm of thoracic aorta just above diaphragm.

CASE REPORTS

CASE 1.—A white man, 60 years old, was admitted to Methodist Hospital on Oct. 11, 1959, because of severe dyspnea. A rounded mass in the upper posterior part of the mediastinum, pushing the trachea backward and to the right, was noted in plain roentgenograms of the chest (Fig. 1).

On Oct. 13, 1959, with the patient in the supine position, a long anterior thoracic incision was made in both third intercostal spaces and extended across the sternum (Fig. 2, *a*). Retraction of the wall of the chest and separation of the aortic arch from the adjacent structures exposed a sacciform aneurysm, approximately 8 cm. in diameter, arising from the entire posterior wall of the aortic arch displacing the trachea backward and to the right (Fig. 2, *b*). The innominate and left common carotid arteries arose as a common trunk from the uninvolved strip of aorta just superior to the aneurysm. Before the aneurysmal sac could be removed, it was necessary to isolate the aortic arch and the origins of the great vessels. This was done by insertion of an external bypass shunt of knitted Dacron from the side of the ascending aorta proximally to the sides of the descending thoracic aorta and the innominate/left common carotid artery trunk distal to the region of operation (Fig. 2, *c*).

With the shunt functioning, clamps were placed across the aorta proximal and distal to the aneurysm, across the trunk of the innominate/left common carotid artery between the shunt and aorta, and across the left subclavian artery just distal to its origin from the aorta. With the handles of the clamps placed across the ascending aorta and the common arterial trunk, the aortic arch was rotated forward and to the left (Fig. 2, *d*). This exposed the posterior surface of the arch and the origin of the aneurysm. The aneurysm was entered and the clot removed. Excision of the thin wall of the aneurysm left an oval defect in the entire posterior aortic circumference extending to within 5 mm. of the origin of the great vessels. This defect was closed by inserting a patch graft tailored from a regular knitted Dacron aortic graft. Two 3-0 arterial sutures were first placed through the patch and then out through the edge of the defect, one superiorly and the other inferiorly, holding the patch loosely in place. Then, with the use of first one and then the other suture, the patch was inserted into the defect by a continuous over-and-over suture (Fig. 2, *e*).

Circulation was restored through the normal channels by releasing the clamps and the bypass shunt was removed. To simplify removal of the bypass shunt and to prevent constriction, a small segment of shunt was left in place at each anastomotic site for suturing. Clamps were placed across the tubes at each anastomotic site and the tubes were transected approximately 2 mm. distal to the clamps. The small remnants of the tubes were then closed by simple over-and-over sutures placed just distal to the clamps (Fig. 2, *f*). The incision in the chest was closed, and a standard tracheostomy completed the operation.

The postoperative course was uneventful. Dyspnea was completely relieved, and the tracheotomy tube was removed on the seventh postoperative day. At this writing, 9 months after operation, the patient has resumed normal activity, including full-time employment as an electrician.

CASE 2.—A Negro man, 62 years old, was admitted to the hospital on Nov. 29, 1959, because of pain in the left lower side of the chest of 6 months' duration. A rounded mass, containing calcium, in the left side of the chest just above the diaphragm and behind the heart was demonstrated on roentgenography (Fig. 3, *a* and *b*). At operation on Nov. 25, 1959, a sacciform aneurysm, measuring approximately 15 cm. at its greatest diameter, was found arising from the descending thoracic aorta just above the diaphragm, with the neck of the aneurysm involving the lateral half of the aortic wall. The aneurysm was excised and replaced with a Dacron patch graft (Figs. 4-6). The postoperative convalescence was uneventful and the patient has resumed full-time employment.

CASE 3.—A white man, 66 years old, was admitted to Methodist Hospital on Feb. 17, 1960, because of a slowly growing mass which was thought to be a thoracic aneurysm. On roentgenography of the chest, calcification of the arch of the aorta and a large, rounded, lobulated mass just above the left hilum, intimately associated with the aortic arch, were demonstrated (Fig. 7, *a* and *b*). This was confirmed by angioaortography. On Feb. 19, 1960, a sacciform aneurysm of the aortic arch, just distal to the left subclavian artery, was excised and the defect was repaired with a Dacron patch graft (Fig. 7, *c* and *d*) as described in Case 1. A temporary shunt from the left subclavian artery to the descending aorta was used. The postoperative course was uneventful, and the angioaortogram made after operation showed normal aortic continuity and function (Fig. 7, *e*). Follow-up observation 3 months later revealed the patient to be in good condition and able to resume his normal activities.

CASE 4.—A white man, 58 years old, was admitted to Methodist Hospital on July 27, 1960, for excision of a thoracic aneurysm (Fig. 8, *a*). On angioaortography a localized saccular aneurysm in the junction of the upper and middle thirds of the descending thoracic aorta was demonstrated (Fig. 8, *b*). This was excised and the resultant defect in the aorta repaired by suture of a Dacron acrylate amide patch, according to the technique previously described (Fig. 8, *c*, *d*, and *e*). The postoperative convalescence was uneventful and the patient was discharged from the hospital in good condition. A postoperative angioaortogram revealed restoration of normal continuity and function in the aorta (Fig. 9).

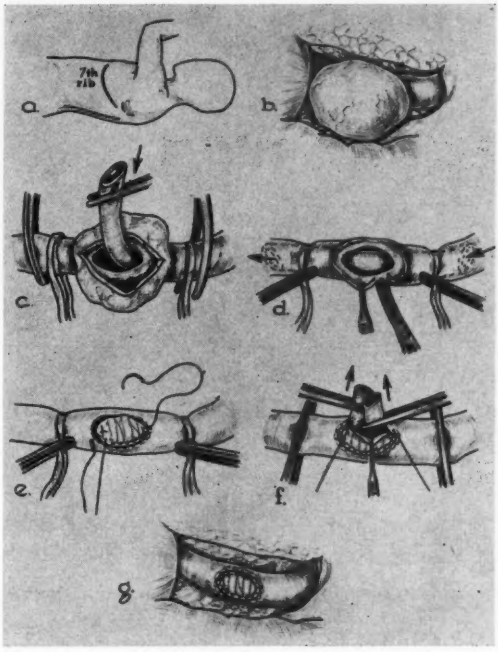

Fig. 4.—Drawing showing method of patch graft repair used in Case 2 in which circulation is maintained during repair by means of a temporary internal shunt. The aneurysm *(b)* was exposed through a low posterolateral incision *(a)*. After mobilization of the aorta above and below the aneurysm, the lesion was incised, and an internal shunt made of Tygon tubing, 20 cm. long and 2 cm. in diameter, was inserted *(c)*. Umbilical tapes which had previously been looped around the aorta proximal and distal to the lesion were tightened about the tube *(d)* and circulation was established through the tube by removal of the clamps. With the tube in place and functioning, the aneurysmal sac was removed and the defect partially closed with a patch graft *(e)*. To remove the shunt *(f)*, clamps were placed across the aorta above and below the region of operation and the tube was cut between the clamps. First one segment of tube and then the other was removed and, with the aortic clamps in place, insertion of the patch was completed. Circulation was restored by removal of the aortic clamps *(g)*.

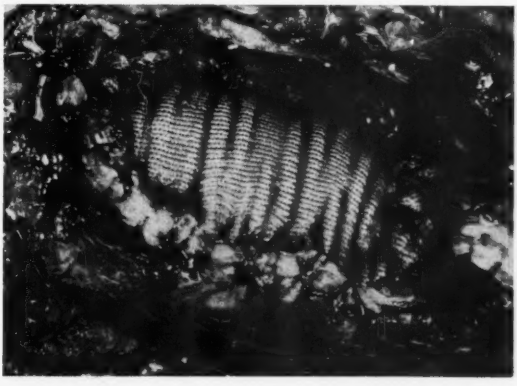

Fig. 5.—Photograph at operation in Case 2 showing patch graft in place.

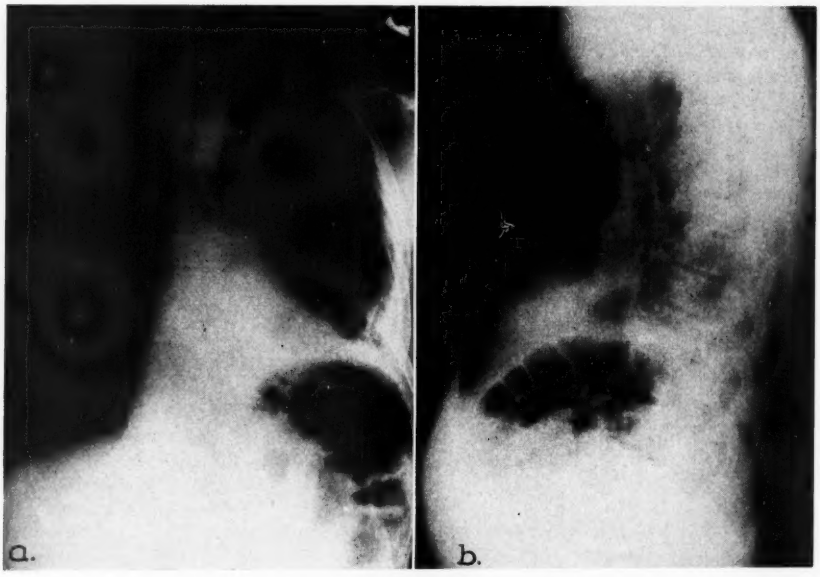

Fig. 6.—*(a)* Posteroanterior and *(b)* lateral roentgenograms of chest in Case 2 made after operation.

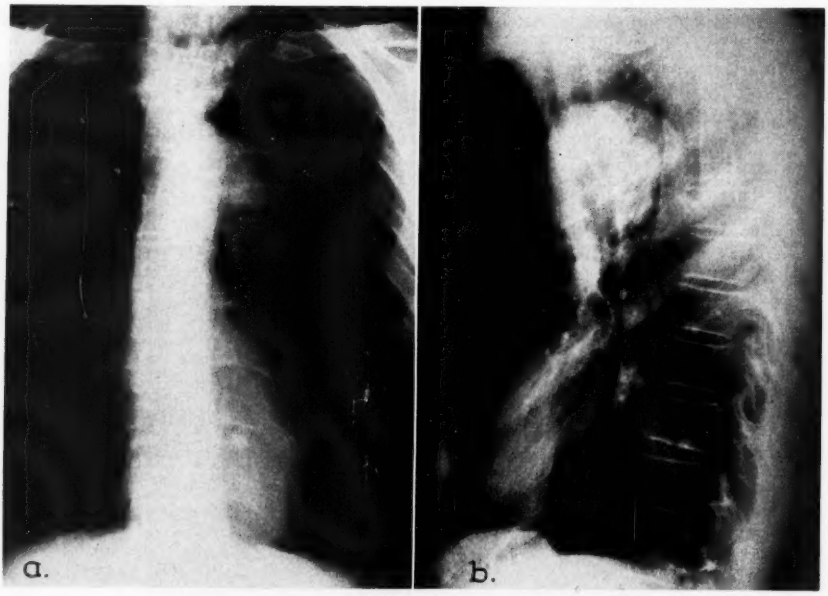

Fig. 7.—*(a)* Posteroanterior and *(b)* lateral roentgenograms showing large sacciform aneurysm in patient described in Case 3. The aneurysm was located in the aortic arch just above the left hilum and was treated by excision and patch graft repair, using temporary plastic tube shunt extending from left subclavian artery to aorta distal to lesion.

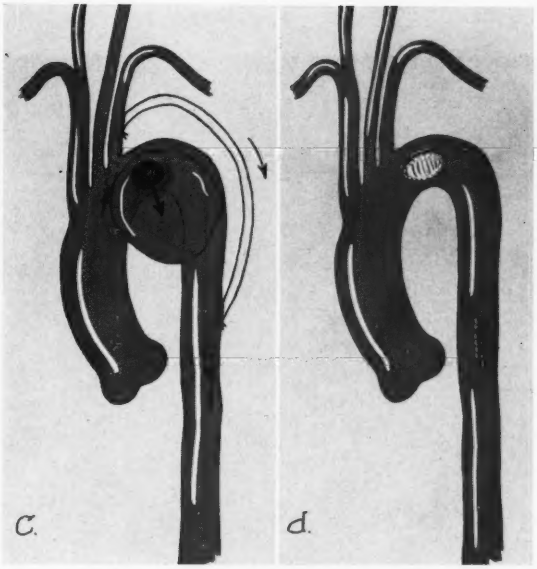

Fig. 7.—Cont'd. *(c)*, Drawing which shows location of sacciform aneurysm in aortic arch and method of repair. Temporary circulation was maintained by means of a plastic shunt inserted proximal to the aneurysm through a small opening in the left subclavian artery and distally through a similar opening in the descending thoracic aorta. Occluding clamps were then placed across the aorta proximal and distal to the aneurysm which was then excised and the defect in the aorta repaired by means of a Dacron knit patch graft. *(d)*, Drawing showing completed procedure of patch graft repair and suture closure of incisions in left subclavian artery and descending thoracic aorta.

Fig. 7.—Cont'd. *(e)* Angioaortogram made after operation showing normal continuity and function of thoracic aorta.

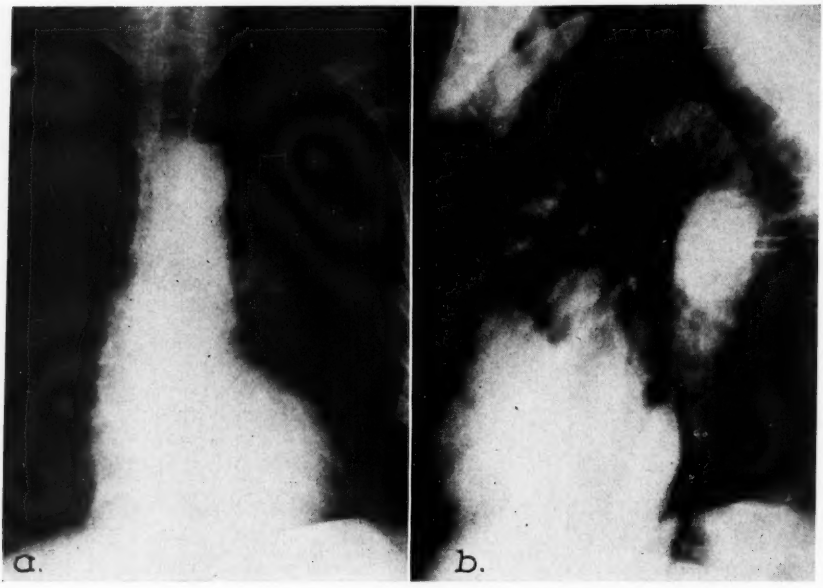

Fig. 8.—*(a)* Posteroanterior roentgenogram and *(b)* angioaortogram of chest of patient described in Case 4 showing sacciform aneurysm in mid-portion of descending thoracic aorta.

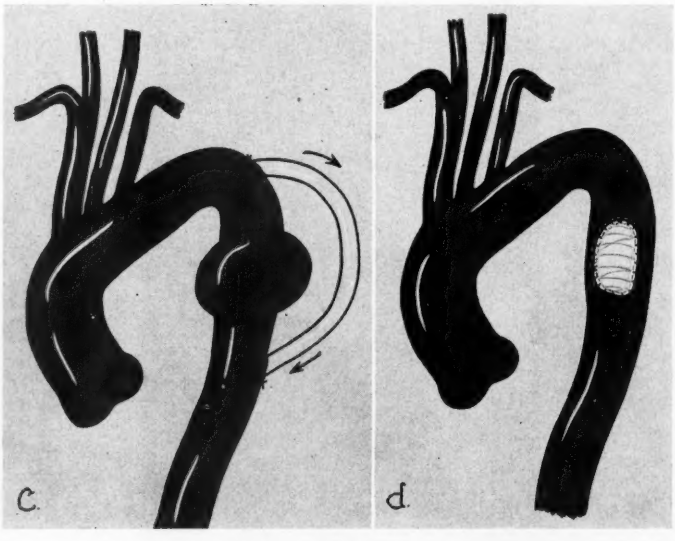

Fig. 8.—Cont'd. *(c)* Drawing which shows method of providing temporary circulation using plastic shunt inserted through small opening in descending thoracic aorta above and below aneurysm. *(d)* Drawing shows completed procedure of patch graft repair of aorta after excision of aneurysm and suture closure of openings in aorta after removal of shunt.

Fig. 8.—Cont'd. *(e)* Photograph made at operation shows completed patch graft repair of aortic defect after removal of aneurysm.

Fig. 9.—Angioaortogram made in Case 4 after operation shows restoration of normal continuity and function of descending thoracic aorta.

CASE 5.—A Negro man, 52 years old, known to have syphilis was admitted to the hospital Sept. 1, 1960, because of back pain. A plain roentgenogram of the spine showed erosion of the anterior surface of the first and second lumbar vertebrae (Fig. 10, *a* and *b*), and a large syphilitic aortic aneurysm was excised on Sept. 21, 1960 (Fig. 10, *c*). The distal thoracic and upper abdominal aortic segments were exposed through a thoracoabdominal incision made on the left side. A large sacciform aneurysm was found involving the posterior half of the aortic circumference opposite the origins of the celiac axis, the superior mesenteric artery, and the right renal artery. Clamps were placed proximal and distal to the lesion.

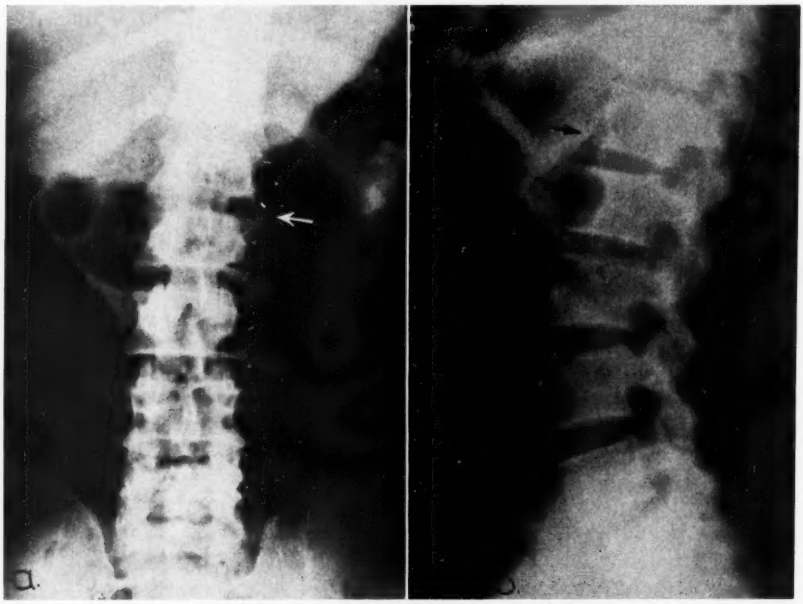

Fig. 10.—Illustration which shows application of patch graft angioplasty in the treatment of sacciform aneurysm of the upper abdominal aorta. *(a)* Anteroposterior roentgenogram showing destruction of left transverse process of first lumbar vertebra and abnormal calcification opposite first and second lumbar vertebrae. *(b)* Lateral roentgenogram showing bone erosion of first and second lumbar vertebrae.

The aneurysm was entered and its wall excised leaving an oval-shaped defect involving the entire posterior half of the aortic circumference opposite the origin of the great abdominal vessels. This defect was closed using a patch graft as previously described. A shunt was not employed since aortic circulation was arrested for only 20 minutes.

DISCUSSION

This method of excision and repair of large sacciform aneurysms of the aorta not only has proved technically feasible, as evidenced by the cases herein reported, but also has a number of advantages over previously employed methods. For one thing, the extent of dissection is appreciably reduced and the aorta is reconstructed by simple circular anastomosis in the side of the aorta. This obviates the need of multiple anastomoses, which are required if a tubular graft is inserted, particularly in patients with involvement of the aortic arch

and the upper abdominal aorta. The relative simplicity of the operation is evidenced by the fact that the amount of blood lost and the duration of the operation were approximately one third of those associated with segmental excision and graft replacement.

As in excisional therapy of fusiform aneurysms of the thoracic aorta, performance of local excision of thoracic aortic aneurysms with patch graft repair requires isolation of the involved segment from the systemic circulation.

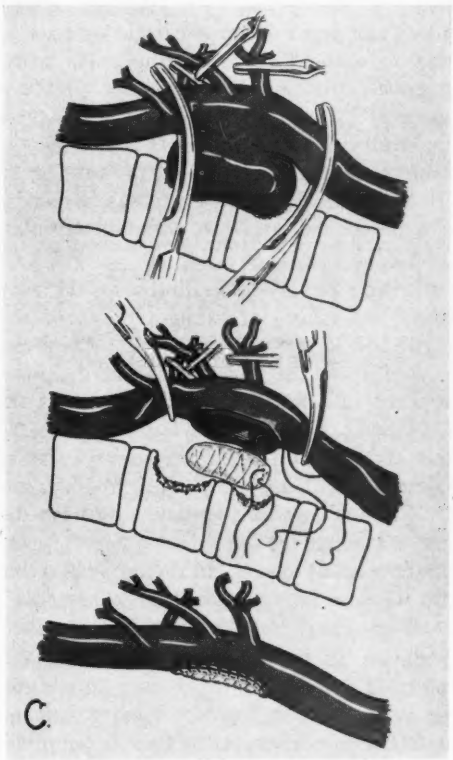

Fig. 10.—Cont'd. *(c)* Drawings which illustrate technique of excising aneurysm and closing defect using patch graft.

This is associated with certain potential dangers including, particularly, increased vascular resistance upon the heart causing left ventricular strain and heart failure and ischemic damage to the tissues distal to the occluded segment. To overcome these hazards, one of several methods may be employed, depending upon the location and extent of the lesion.

In aneurysms that do not involve the proximal segment of the ascending aorta, relatively normal aortic circulation can be maintained during the entire operation by means of the temporary bypass principle, with use of a Dacron bypass shunt as in Case 1. With the availability of the Dacron tube as a vascular

replacement it is sometimes desirable to convert the temporary Dacron shunt into the permanent graft. This is exemplified by a case previously reported and illustrated[8] in which a large sacciform aneurysm with a wide neck involved the transverse arch at the origin of the innominate and left common carotid arteries. In order to maintain normal aortic circulation during exclusion of this segment of the aortic arch, the trunk of a bifurcation knit Dacron graft was attached by end-to-side anastomosis to the descending limb of the aortic arch and the two branches of the graft were attached, respectively, by similar anastomoses to the left and right common carotid arteries. A tubular Dacron graft was then used to connect the ascending aorta with the trunk of the bifurcation Dacron graft. In this manner, normal circulation was maintained through these bypass grafts during exclusion of the transverse arch, permitting excision of the large aneurysm and patch graft repair of the resultant defect in the arch. At the completion of this procedure, the tubular graft connecting the ascending aorta with the bifurcation knit graft was removed and the bifurcation graft remained as a permanent graft to maintain circulation to the carotid arteries.

For aneurysms arising in the descending thoracic aorta distal to the left common carotid artery, some form of temporary bypass may be employed, depending upon the type and location of the lesion. The pump bypass method in which blood is removed from the left auricle and pumped through a plastic cannula inserted upward into the left femoral artery is the most satisfactory method for lesions involving the left subclavian artery or extending just distally along the descending thoracic aorta. If the aneurysm is well localized to the mid-portion of the descending thoracic aorta, a temporary internal shunt may be used, as in Case 2. For well-localized aneurysms arising distal to the left subclavian artery, another method for temporary bypass consists in insertion of a plastic catheter through a small opening in the left subclavian artery proximally as in Case 3, or into the descending thoracic aorta immediately above the aneurysm, as in Case 4, and into the descending thoracic aorta distally.

Arrest of circulation in the abdominal aorta above the major visceral branches is well tolerated for periods up to over 30 minutes. The application of local excision and patch graft angioplasty in the treatment of sacciform aneurysms of the upper abdominal aorta, as in Case 5, simplifies operation to such an extent that shunts are not required to maintain circulation to the kidneys and other abdominal viscera during operation. This method of therapy avoided the need for segmental excision and graft replacement. Operation was completed in 20 minutes, thus eliminating the need for shunts.

SUMMARY

Simple excision of sacciform aneurysms distal to the occluding clamp and closure of the aortic opening by suture, as employed in lesions involving a small part of the aortic circumference and attached by a narrow neck, is not applicable to aneurysms with relatively large necks whose sacs roll over to incorporate much of the aortic wall. It is difficult, if not impossible, to apply

an occluding clamp across the base of such aneurysms without causing severe constriction or complete occlusion of the aortic lumen. Moreover, repair of these aneurysms may cause severe encroachment on the normal aortic lumen. Therefore, complete excision of the involved aortic segment with graft replacement may be necessary, a procedure of considerable magnitude. It has proved possible to eradicate such lesions by a much simpler procedure, consisting of excision of the aneurysmal sac and closure of the aortic opening with a patch graft. This has the advantage of being relatively simple, as evidenced by the great reduction in the amount of blood lost and in the duration of the operation in the 5 cases herein reported.

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THROMBOEMBOLIC COMPLICATIONS FOLLOWING INSERTION OF THE HUFNAGEL PROSTHESIS

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HIRSCHBOECK[1] first observed that the surface properties of methyl methacrylate inhibited the coagulation of blood. This was confirmed by Hufnagel[2] who found that properly designed tubes of this material could be used to replace portions of the aorta. He attributed the inhibition of blood clotting to the non-wettability of the surface of the plastic material, a property which was further enhanced when the surface was highly polished.[2]

Experimentally, necrosis of the wall of the aorta was uniformly found where continuous circumferential ligature was used.[2-4] Multiple-point fixation for the prosthesis within the aorta appeared to obviate the development of fatal hemorrhage from aneurysm, or necrosis of aortic wall.

In May, 1954, Hufnagel and co-workers[5] described the results obtained in 23 patients in whom a methyl methacrylate valve had been inserted in the descending thoracic aorta for the partial correction of aortic insufficiency. The complications reported were those of subacute bacterial endocarditis, cardiac arrhythmias, myocardial failure, and reactivation of a rheumatic process. No cases were reported in this series in which there was any evidence to suggest clotting complications in or about the prosthesis. On the other hand, Conklin and co-workers[6] observed that a high incidence of early and late thromboembolic complications occurred in 5 of their 21 patients in whom a Hufnagel prosthesis was used. The period of onset was from 3 months to 18 months postoperatively.

Among 16 such operations performed in recent years at National Jewish Hospital and affiliated institutions in Denver, 5 patients have developed thromboembolic complications. In the experience of the authors, this problem has been frequent and serious enough to limit recommendations for insertion of this prosthesis. The case records of 3 patients are considered as representative and are being reported to stress the serious problem of thromboembolism following the insertion of the valve.

CASE REPORTS

CASE 1.—(NJH No. 12036.) The patient was a 22-year-old white man, a farm laborer, who was admitted to National Jewish Hospital for the first time on Jan. 18, 1957. At

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the age of 6, and again at 14, he had had migratory polyarthritis associated with fever. He remained in comparatively good health until 1953 when he began to experience increasingly frequent episodes of upper abdominal and lower chest pain, aggravated by exercise and relieved by rest. An irregularity of the cardiac rhythm was first noticed at this time. In 1954, following a tooth extraction, he developed fever and malaise and *Streptococcus mitis* was isolated from multiple blood cultures. Following the disappearance of this organism from the blood, the patient noticed progressive incapacitation because of exertional dyspnea and chest pain. He was unable to work and it was because of these complaints that he was admitted to National Jewish Hospital.

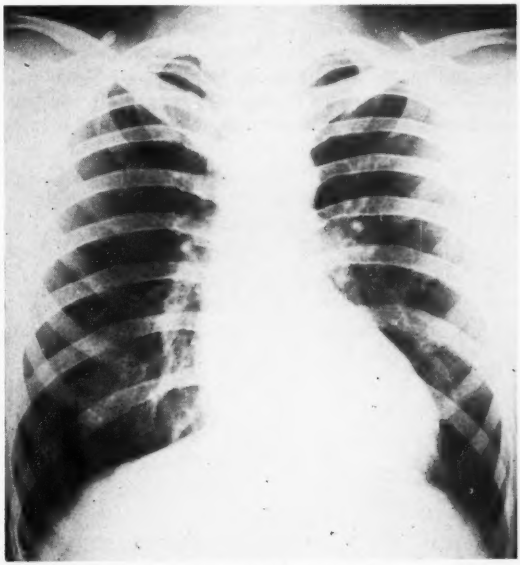

Fig. 1.—Posteroanterior roentgenogram of the chest. The over-all heart size is increased with rounding of the right ventricle and prominence of the ascending aorta. There is slight congestion of pulmonary vascular pattern.

Physical examination on admission revealed a pulse of 84 per minute and regular. Blood pressure was 126/40 mm. Hg. The heart was overly active. The point of maximal impulse was in the sixth intercostal space, in the anterior axillary line. There was a visible systolic thrust at the apex and a prominent left ventricular "rock." No thrills or shocks were palpable. Corrigan pulses, pistol shot femoral pulses, prominent carotid and capillary pulses, pulsating central retinal arteries, and head bobbing were all noted. On auscultation, a Grade 2-3 (on the basis of 6), medium-pitched, blowing systolic murmur was heard over the entire anterior precordium, loudest at the second right interspace with radiation into the neck vessels. A Grade 2-3, high-pitched, blowing early diastolic decrescendo murmur was audible at the second right interspace and along the left sternal border. The aortic second sound was not audible, whereas the first mitral sound was muffled. The pulmonic second sound was of normal intensity and not particularly split.

Cardiac roentgenograms revealed that the left ventricle was markedly enlarged. The ascending aorta was prominent. The left atrium was slightly prominent. Slight congestion of pulmonary vascular pattern was present. There was no evidence of enlargement of the right side of the heart (Fig. 1). On fluoroscopy a marked increase in the amplitude of pulsations of the cardio-aortic silhouette was observed.

The electrocardiogram revealed definite evidence of left ventricular enlargement and suggestive evidence of digitalis effect (Fig. 2).

Operation for aortic insufficiency was initially deferred and the patient was discharged on medical management. He was readmitted 2 months later because in the interim he had become more incapacitated with more exertional dyspnea and chest pain.

On March 27, 1958, operation for the insertion of the prosthetic valve was performed. The immediate postoperative period was uneventful and he was discharged to be followed at 3-month intervals in the out-patient department.

The initial postoperative course appeared to be favorable with diminution of chest pain and dyspnea. After operation the patient was able to return to work. On Jan. 24, 1958, he was readmitted as an emergency to the hospital for the third time, shortly after the onset of coldness, pain, and numbness in the left arm which had occurred while typing. The skin of the left hand was pale, with moderate duskiness of the nail beds as compared with the opposite side. The pulses in the left brachial, radial, and ulnar arteries were not felt. The impression was that acute occlusion of the left axillary artery had occurred. Treatment with papaverine intramuscularly (gr i every 6 hours) was instituted.

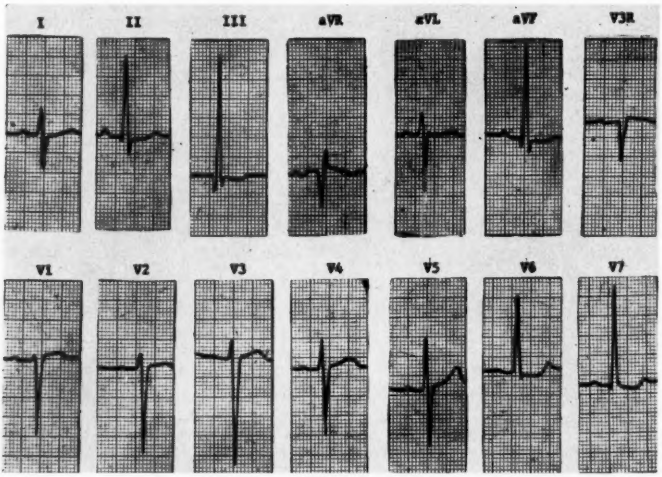

Fig. 2.—The electrocardiogram shows evidence of left ventricular hypertrophy; the pattern is suggestive of digitalis effect.

A left stellate ganglion block was performed and, although there was a good Horner response, no appreciable change in skin temperature or circulation was noted. On Jan. 27, 1958, warfarin sodium (Coumadin) therapy was started. The tenderness and pain at the site of the occlusion gradually disappeared and the coldness and numbness of the left arm improved. Pulsations of the arteries of the left arm did not return. Long-term use of anticoagulants was recommended.

Comment: A 22-year-old man was incapacitated by dyspnea and chest pain as the result of rheumatic aortic valvular insufficiency. The insertion of a Hufnagel valve stabilized the condition for 9 months and even appeared to produce a limited remission of symptoms. This improvement was temporarily interrupted by a thrombotic or embolic phenomenon occluding the left subclavian artery. The proximity of the prosthesis to the latter makes it likely that there was a gradual retrograde growth of a thrombus. The patient is presently being maintained on long-term anticoagulant therapy.

CASE 2.—(NJH No. 12943.) The patient was a 26-year-old Spanish-American housewife who was admitted to National Jewish Hospital for the second time on May 6, 1958. She had had severe chorea at the age of 7, and a heart murmur was first heard at that time. She remained relatively well for 17 years until 1956 when she noticed the onset of recurrent severe constrictive chest pains lasting 10 to 30 minutes, occurring primarily during emotional upsets or exercise. In May of 1957 she began experiencing recurrent episodes of paroxysmal nocturnal dyspnea. In July she was treated for congestive cardiac failure with digitalis and mercurial diuretics. At the time of admission she was severely incapacitated by chest pain and dyspnea.

Physical examination on admission revealed a pulse of 100 per minute, regular and of Corrigan type. Arterial pulsations of wide amplitude were noted in the neck, subclavian arteries, and suprasternal notch. There was a prominent thrust at the apex of the heart. The point of maximal impulse was visible and palpable in the sixth intercostal space just outside the anterior axillary line. A systolic thrill was present at the second right interspace. On auscultation, a prominent "to-and-fro" murmur was heard over the entire precordium, loudest at the third intercostal space along the left sternal border. The systolic component was harsh, medium-pitched, Grade 4 (on the basis of 6), transmitted to the neck vessels, and the diastolic component was blowing, high-pitched, decrescendo, Grade 3, best heard at the third intercostal space. Both the pulmonic second sound and the mitral first sound were muffled.

The electrocardiogram revealed marked left ventricular hypertrophy, first degree atrioventricular block, and digitalis effect.

Roentgenograms revealed the left ventricle to be moderately enlarged. Fluoroscopy disclosed wide amplitude pulsations of the aorta. Minimal enlargement of the left atrium was observed after a barium swallow. The lung fields displayed the bilateral exudative pattern seen in acute pulmonary edema.

The impression was rheumatic heart disease with severe aortic valvular insufficiency and congestive cardiac failure.

On July 13, 1957, after the congestive failure had been adequately treated with digitalis and mercurial diuretics, operation for the insertion of the valve was performed. The immediate postoperative course was uneventful, and she was discharged on Oct. 5, 1957, with instructions to return at regular 3-month intervals to the cardiac out-patient department. The initial course appeared to be favorable with less dyspnea and chest pain.

At 7:30 A.M. on March 18, 1959, she awakened suddenly with pain and numbness in the left foot; and she found she was unable to walk properly. On physical examination the leg was cold and discolored, with absent popliteal, dorsalis pedis, and posterior tibial pulses. A diagnosis of acute femoral artery occlusion secondary to an embolus from the prosthesis was made and an emergency embolectomy was performed. She was subsequently placed on anticoagulant therapy, with the prothrombin level being maintained between 20 and 30 per cent on a daily dosage of 2.5 to 5.0 mg. of warfarin sodium (Coumadin). By April 9, 1959, all pulses in the left lower limb were palpable and fairly strong. On discharge she had complete return of function of the left leg.

Five months later she was admitted to another hospital with an embolus to her right leg. Though discharged from National Jewish Hospital on warfarin sodium, she had not taken it regularly and no prothrombin studies had been done.

Comment: This 26-year-old Spanish-American housewife suffered from aortic valvular insufficiency secondary to rheumatic heart disease. Prognosis prior to operation was believed to be poor. Insertion of the prosthesis had partially alleviated the general symptomatology for approximately 18 months when an acute left femoral embolization occurred. A second embolus occurred 5 months later.

CASE 3.—(SLH No. 157806.) The patient was a 21-year-old white man who had had acute rheumatic fever at the age of 13. He was admitted to the hospital on May 22, 1957. He had a known heart murmur since that time and was advised to reduce his physical activity. One year before admission he first noticed a marked decrease in his strength as well as increasingly severe exertional dyspnea.

Physical examination on admission showed a markedly over-active heart with a left ventricular thrust. There was a loud systolic and diastolic murmur of "to-and-fro" nature over the entire anterior precordium, maximum at the cardiac base. Blood pressure was 195/40/0 mm. Hg. The pulse was 82 per minute, regular and Corrigan in type.

Roentgenograms revealed marked enlargement of the left ventricle. Fluoroscopy was not performed.

Fig. 3.—The completely thrombosed prosthesis removed from Case 3.

The electrocardiogram showed definite left ventricular enlargement.

On May 29, 1957, the valve was inserted in the descending thoracic aorta. Initial course appeared to be favorable with less dyspnea noted. In June, 1958, he developed minimal pain in the left leg followed by typical symptoms of intermittent claudication of a rather mild nature. Oscillometric studies revealed no definite evidence of an arterial block. The patient noticed at this time that the clicking of the valve had become somewhat muffled. On Feb. 21, 1959, he suddenly developed severe pain in both legs and rapidly went into profound shock. He also noted at this time the complete silence of the previously muffled click of the valve.

Occluding thrombosis of the prosthesis was diagnosed, and an emergency exploratory thoracotomy was performed. The diagnosis was confirmed and the prosthesis removed. The patient died before another valve could be inserted. Fig. 3 shows the prosthesis which was found to be completely thrombosed upon surgical removal.

Comment: This 21-year-old man, who suffered rheumatic heart disease complicated by severe aortic insufficiency for at least 7 years of his life, sustained a clinical improvement for about 15 months after operation. In contrast to the previous 2 cases cited, there were no embolic phenomena but complete thrombosis of the internal mechanism of the prosthesis had occurred.

DISCUSSION

The highly polished surfaces of the valve increase its non-wettability, thereby decreasing likelihood that the blood as it passes through the valve will undergo coagulation.[1, 2] It is probable that other mechanisms within the

prosthesis itself should be considered as possible causative agents for the development of thromboembolic phenomena.

The constant pounding of the ball might cause small indentations on the surface. This might form a potential nidus for the deposition of platelets and ensuing thrombus formation, somewhat analagous to vegetation formation in subacute bacterial endocarditis. Another undocumented possibility is the precipitation of fibrin and its precursors secondary to the constant trauma to the blood stream within the prosthesis.

The finding of atherosclerotic changes in the vessels distal to the prosthesis in another recently necropsied case also may be important. In this case premature atherosclerosis apparently acted as the substrate for thrombus formation. It is our impression that the low mean intra-arterial pressure found in aortic insufficiency is probably protective against atherosclerosis since patients dying of aortic insufficiency prior to the advent of cardiac surgery often were free of atherosclerotic changes. The prosthetic valve eliminates the low diastolic pressure in vessels distal to the valve and could conceivably accentuate atherosclerotic changes.

In view of the experiences presented, the authors deem it advisable to institute anticoagulant therapy in all patients in the immediate postoperative period following insertion of the valve and to maintain anticoagulants for an indefinite period. Our long-range experience with patients described in this report suggests that the thromboembolic complications which can develop should be seriously considered before the operation is recommended.

SUMMARY

Insertion of the prosthetic valve was performed in 16 patients with severe aortic insufficiency. The case records of 3 of the 5 patients who developed late thromboembolic complications are reported. Although the series studied was small, the percentage of long-range adverse effects after insertion of the Hufnagel valve was high. This appears to limit the usefulness of such operative procedures.

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INCIDENCE OF CARDIAC ARRHYTHMIAS FOLLOWING NONCARDIAC THORACIC SURGERY

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IN THE PAST two decades the indications for thoracic surgery have been broadened by refinements in diagnostic and surgical techniques so that thoracic surgical procedures are now widely and frequently performed. Although meaningful figures are not available for the incidence of arrhythmias following general surgery, it has been the opinion of clinicians from the advent of modern thoracic surgery to the present time that the incidence of arrhythmias is higher following thoracic surgery.[1]

We were able to find only six reports[2-7] concerning the incidence of arrhythmias following noncardiac thoracic surgery and none dealt with an unselected series of patients. The present study was done to estimate the incidence of cardiac arrhythmias in a randomized sample of 1,100 patients that underwent noncardiac thoracic surgery from 1948 to 1958 at The George Washington University Hospital.

MATERIAL AND METHODS

A retrospective review of 338 medical records, or 30.7 per cent of the total 1,100 patients, was conducted to extract the following information: (1) age, (2) sex, (3) race, (4) diagnosis, (5) pre-existing heart disease, (6) location of the intrathoracic lesion, (7) type of operation, (8) type of anesthesia, (9) treatment, and (10) occurrence of arrhythmia.

Charts of every year of the period from 1948 to 1958 were reviewed. One or more electrocardiograms were available for review in every case in which an arrhythmia was noted to have occurred. The arrhythmias present in the group were classified on the basis of the electrocardiograms as follows: (1) sinus tachycardia (with a rate of 150 per minute or more), (2) premature ventricular contractions, (3) premature atrial contractions, (4) atrial fibrillation, (5) atrial flutter, (6) atrioventricular block, and (7) ventricular tachycardia. Of the 338 patients, 203 were males and 135 were females. The average ages for males and females were 46 and 44 years, respectively.

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RESULTS

A total of 15 patients, or 4.4 per cent of the 338, had an arrhythmia following surgery. Seven were males and 8 were females, with an average age of 59 years and an age range of 42 to 71 years. One third (5) of the patients who developed an arrhythmia postoperatively died shortly after its appearance. Three of these had been digitalized. Of the 10 patients who did not die, 4 were digitalized.

Six of the 15 patients with an arrhythmia, or 1.4 per cent of the 338 studied, had sinus tachycardia with rates of 150 or more per minute. Their average age was 53 years. Half of them died shortly after the appearance of the arrhythmia. The remaining group of 9 patients, 2.6 per cent of the 338 studied, had an average age of 63 years; 2 of this group died.

The frequency of occurrence and the types of arrhythmia which occurred are listed in Table I. The most frequent alterations of rhythm encountered in this group were premature ventricular and premature atrial contractions. Atrial fibrillation occurred in 2 cases, and second degree A-V block (2:1) occurred in one instance.

TABLE I. TYPES OF ARRHYTHMIA

	OCCURRENCES	PATIENTS
Premature ventricular contractions	6	3
Premature atrial contractions	4	3
Atrial fibrillation	2	2
A-V block (2:1)	1	1
Sinus tachycardia	6	6
Totals	19	15

The diagnoses in the patients with arrhythmia are listed in Table II. Eight of the 15 patients (53 per cent) with arrhythmia had carcinoma. Other diagnoses in the group with arrhythmia included: neurofibroma, pulmonary tuberculosis, pericardial cyst, achalasia, and esophageal varices.

TABLE II. DIAGNOSES IN PATIENTS WITH ARRHYTHMIAS

	PATIENTS	PER CENT
Bronchogenic carcinoma	6	40.0
Esophageal carcinoma	2	13.3
Neurofibroma	1	6.6
Pulmonary tuberculosis	2	13.3
Pericardial cyst	1	6.6
Achalasia	1	6.6
Esophageal varices	2	13.3
Totals	15	100.0

Of the total sample of 338 patients, 82 or 24.2 per cent had carcinoma (Table III). The incidence of carcinoma in the group under 40 years of age was composed of 8 patients, or 7.8 per cent of the total. In the group

TABLE III

AGE	PATIENTS WITHOUT ARRHYTHMIA (NO.)	PATIENTS WITH ARRHYTHMIA (NO.)	PATIENTS WITH CARCINOMA (NO.)	PATIENTS WITH CARCINOMA AND ARRHYTHMIA (NO.)
Under 40	103	0	8 (7.8%)	0
41-50	67	3	10	1
51-60	91	5	40	2
61-70	56	4	22	3
71-80	5	3	2	2
81-90	1	0	0	0
Over 40	220	15 (6.3%)	74 (33.6%)	8 (3.6%)
Totals	323	15 (4.4%)	82 (24.2%)	8 (2.3%)

over 40 years, the incidence was 74 patients or 33.6 per cent. When the 103 patients under 40 years of age are excluded, the incidence of arrhythmias in the remaining 235 is 6.3 per cent. The highest percentage of operations were performed in the fifth, sixth, and seventh decades (Table IV). The incidence of arrhythmia and carcinoma was greatest in the sixth and seventh decades.

TABLE IV

DECADES	PATIENTS WITHOUT ARRHYTHMIA (NO.)	PATIENTS WITH ARRHYTHMIA (NO.)	PATIENTS WITH ARRHYTHMIA AND CARCINOMA (NO.)
1-10	8	0	0
11-20	15	0	0
21-30	30	0	0
31-40	50	0	0
41-50	67	3 (20%)	1 (12%)
51-60	91	5 (33%)	2 (25%)
61-70	56	4 (26%)	3 (37%)
71-80	5	3 (20%)	2 (25%)
81-90	1	0	0
Totals	323	15	8

The incidence of arrhythmias in relation to the surgical procedure performed is presented in Table V. The highest incidence of arrhythmias occurred in patients who underwent exploratory thoracotomy. Other procedures

TABLE V. INCIDENCE OF ARRHYTHMIA CLASSIFIED BY TYPE OF OPERATION

	PATIENTS WITHOUT ARRHYTHMIA	PATIENTS WITH ARRHYTHMIA
Exploratory thoracotomy	92	7 (46.6%)
Exploratory thoracotomy and biopsy	76	4 (26%)
Resection of mediastinal mass	21	1 (6.6%)
Pneumonectomy	5	0
Lobectomy	33	2 (13.2%)
Segmental resection	48	1 (6.6%)
Decortication	5	0
Biopsy of pleura	5	0
Resction of blebs and poudrage	17	0
Drainage of empyema	7	0
Hiatal herniorrhaphy	14	0
Totals	323	15

associated with an arrhythmia were exploratory thoracotomy and biopsy, lobectomy, resection of mediastinal mass, and segmental resection. Arrhythmias were not encountered in the patients who underwent pneumonectomy, decortication, biopsy of the pleura, resection of blebs and poudrage or hiatal herniorrhaphy.

No relationship could be established between the presence of an arrhythmia and sex, race, pre-existing heart disease, location of the lesion, or type of anesthesia.

DISCUSSION

From 1943 until 1957 six reports concerning the incidence of arrhythmias in pre-selected cases following noncardiac thoracic surgery have been published.[2-7] Of the 556 reported cases, 72 patients (12.6 per cent) experienced an arrhythmia postoperatively. The incidence varies from 9.9 per cent in Massie's report[4] to 21 per cent in Currens[2] report. In the reported series there were selected groups of subjects who underwent pneumonectomy or lobectomy; patients with carcinoma of the lung or carcinoma of the esophagus; and patients over 40 or in the senior age group.

It is interesting to note that the series with the highest incidence[2] was composed exclusively of patients with the diagnosis of carcinoma of the lung or esophagus. Of the 82 subjects with carcinoma in our study, 8 or 2.3 per cent had arrhythmias. Cohen, Peery, and Evans[10] in 1955 studied 315 deaths from malignant tumors in a series of 1,007 consecutive autopsies at this institution. Fifteen of these patients, or 4.7 per cent, had had arrhythmias before death. These investigators called attention to the frequency of neoplastic invasion of the heart and pericardium of patients with carcinoma elsewhere in the body. They found that 65 subjects out of the 315 had metastases into the heart, pericardium, or both. Fifteen of these 65 (23 per cent) had had arrhythmias before death. In their series, the incidence of cardiac metastases from bronchogenic carcinoma was 18.5 per cent. In our study, 6 of the 8 patients with carcinoma and arrhythmias had bronchogenic carcinoma.

The higest incidence of arrhythmias in Cohen, Peery, and Evan's series with cardiac metastases was in the fourth (13 cases), fifth (21 cases), and sixth (12 cases) decades. All authors seem to agree that age is the most important factor and that the incidence of arrhythmias is higher in the older age group. This was substantiated by our study.

The incidence of arrhythmias in our study is less than that reported in the literature. Since 4 out of the 6 studies in the literature were published before 1952, improvements in the methods of medicine, anesthesia, and surgery may account for our lower incidence. It is also possible that the pre-selection of cases in other studies, especially the ones with carcinoma may have resulted in an apparent higher incidence of arrhythmias after noncardiac thoracic surgery.

The limitations of retrospective studies such as this one and those reported in the literature preclude drawing conclusions regarding the predisposing

factors in the appearance of arrhythmias following thoracic surgery. The need for controlled prospective studies to obtain more meaningful data regarding the incidence of arrhythmias following thoracic surgery and general surgery is obvious after reviewing the literature and our own medical records. The need is highlighted by the poor prognostic implication of a post-thoracotomy arrhythmia. The percentage of deaths in subjects with arrhythmias indicates the serious nature of this complication after surgery.

SUMMARY

A review of 338 records of patients that underwent noncardiac thoracic surgery has been studied retrospectively. The 4.4 per cent incidence of arrhythmias found in this series is lower than that reported in the literature.

No arrhythmias were encountered in the subjects under 40 years of age. When they are excluded from the total, the incidence of arrhythmias is 6.3 per cent. In our series, age and the presence of carcinoma are apparently the two most important predisposing factors in the appearance of arrhythmias following noncardiac thoracic surgery.

One third of the patients who developed an arrhythmia after noncardiac thoracic surgery died shortly after appearance of the arrhythmia despite digitalization or other treatments.

The authors wish to express appreciation to Dr. Paul C. Adkins from the Department of Surgery for his helpful assistance and advice in this study.

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CEREBRAL COMPLICATIONS OF OPEN-HEART SURGERY

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THE EXPERIENCE at the State University of Iowa has been predominantly favorable in a moderately large series of open-heart operations for congenital disease. The total number of operations for both atrial and ventricular defects and anatomic variations thereof is 241 up to July 1, 1959. Of this number, 162 patients were treated using the extracorporeal circuit and the remainder with total body hypothermia. Recently, however, we have become aware of the occasional occurrence of cerebral complications in patients undergoing this type of operation. Since these clinical problems have been dealt with infrequently in the surgical literature, we have reviewed our records through June of 1959 with a view to reporting all such complications.

Our experience with these alarming but usually self-limiting complications has been derived from 12 patients, 2 of whom had the closure of septum secundum defects under hypothermia, and 10 of whom had the correction of various congenital cardiac defects employing extracorporeal circulation. Of the latter group all but 1 had complicated ventricular septal defects and the remaining patient had severe infundibular pulmonic stenosis without a septal defect. One of the 12 patients died and the remaining 11 recovered completely. The cerebral manifestations ranged from protracted somnolence to convulsions and hemiplegia.

Two patients, 1 operated upon under hypothermia and 1 with the use of extracorporeal circulation, experienced a delayed onset of hemiplegia, 8 and 14 days postoperatively, and were thought to have had clot emboli probably originating from the left side of the septal suture line. The other patient operated upon under hypothermia responded poorly in the immediate postoperative period and was noted to have a positive left Babinski sign. He recovered completely within 1 week.

The remaining 9 patients had operations involving the use of extracorporeal circulation. Usually they responded well in the immediate postoperative period and experienced the onset of symptoms on the first postoperative day. This led us to the conclusion that, whatever the initial insult, cerebral edema played an important role. Five had convlusions, usually Jacksonian in type. Six, including 4 of those with convulsions, had hemiparesis. One was extremely lethargic and had a deviation of his eyes to the right. One was excessively somnolent for

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3 days but had no localizing signs. One of these 9 patients never responded, had numerous convulsions and right hemiparesis, and died on the third postoperative day.

In attempting to find some common factor applying to the 10 patients who had operations employing extracorporeal circulation, we have found a number of possibly pertinent facts. None of the patients had a simple ventricular septal defect. Five had interventricular septal defects and pulmonic stenosis. Two of these were cyanotic. Two had ventricular septal defects with pulmonary artery hypertension. One had a ventricular septal defect with a patent ductus arteriosus and a pulmonary artery pressure of 82/34 mm. Hg. One had a large ventricular septal defect requiring a Teflon patch for closure. The remaining patient had muscular infundibular stenosis requiring the removal of 15 grams of tissue to overcome the obstruction.

Seven of the 9 patients (77 per cent) with ventricular septal defects required patches for closure and 7 of the 9 (77 per cent) required cardiac arrest.

TABLE I. OPERATIVE DATA

PATIENT	PROSTHESIS	ARREST	DURATION OF ELECTROCARDIOGRAM (MIN.)	FLOW RATE (C.C./KG./MIN.)	CARDIAC LESION
Extracorporeal Circulation					
1. D. A.	yes	yes	28	38	Tetralogy of Fallot
2. G. C.	no	no	31	52	Interventricular septal defect and pulmonary artery hypertension
3. V. B.	yes	yes	39	48	Tetralogy of Fallot; cyanotic
4. D. V.	yes	yes	43	52	Tetralogy of Fallot
5. D. W.	yes	yes	30	52	Tetralogy of Fallot plus valvular pulmonary stenosis
6. D. D.	yes	yes	44	50	Interventricular septal defect
7. S. P.	no	yes	27	50	Interventricular septal defect with pulmonary artery hypertension
8. R. R.	yes	yes	62	48	Interventricular septal defect, infundibular and valvular pulmonary stenosis
9. P. P.	yes	yes	37	50	Interventricular septal defect, patent ductus arteriosus, pulmonary artery hypertension
10. B. H.	no	no	46	46	Infundibular pulmonary stenosis

PATIENT	OCCLUSION TIME	RECTAL TEMPERATURE	DIAGNOSIS
Hypothermia			
11. T. S.	6 min., 45 sec.	29.8° C.	Ostium secundum defect
12. D. P.	6 min., 30 sec.	30° C.	Ostium secundum defect

The average length of the extracorporeal circulation in the 10 cases was 39 minutes. These figures reflect the severity of the disease more effectively when compared with the average applicable figures at this institution. Up to July 1, 1959, 132 ventricular septal defects have been closed. Thirty-four (25 per cent) of these required the use of prosthetic patches and 45 (34 per cent) necessitated cardiac arrest. The average duration of extracorporeal circulation has been 25 minutes, ranging from 20 minutes in ventricular septal defects without pulmonary artery hypertension to 40 minutes in cyanotic patients with ventricular septal defects and pulmonic stenosis.

Our use of extracorporeal circulation is quite conventional. The DeWall bubble oxygenator with Sigmamotor pumps is used. The tubing is disposable and is new for each case. The defoaming chamber is sprayed with Antifoam A.* The oxygenator is assembled under aseptic conditions by a technician just prior to surgery and is calibrated to deliver roughly 50 c.c. of heparinized blood per kilogram of body weight per minute. The left subclavian artery is usually used for arterial cannulation. The artery and its first branch are ligated prior to division.

Our use of hypothermia involves immersion of the anesthetized patient in a bathtub filled with ice until the rectal temperature drops from 0.5° to 1.0° C. The patient is then placed on the operating table on a heating blanket. The temperature reaches desirable levels of about 30° C. rectally at just about the time when the surgeon is ready to occlude the great vessels. If the curve has not flattened by that time rewarming is started with the blanket and, if necessary, warm saline solution is placed in the thorax.

CASE REPORTS

Extracorporeal Circulation.—

CASE 1.—D. A. (53-11627), a 6-year-old boy, had a large ventricular septal defect and infundibular pulmonic stenosis. The defects were corrected employing a compressed Ivalon patch and potassium arrest. Extracorporeal circulation was employed for 28 minutes at 38 c.c./Kg./min. The postoperative course was uneventful until the eighth postoperative day when the patient became unresponsive, with a right facial paresis, left ptosis, and bilateral Babinski signs. He recovered completely over a 2-week period.

CASE 2.—G. C. (58-4184), a 7-year-old boy, had a ventricular septal defect, complete situs inversis, and a pulmonary artery pressure of 56/19 mm. Hg. The defect was closed by direct suturing. Extracorporeal circulation lasted 31 minutes at 52 c.c./Kg./min. On the first postoperative day the boy was extremely lethargic and had a persistent deviation of his eyes to the right. He recovered completely in 10 days.

CASE 3.—V. B. (54-1775), a 9-year-old girl, had a ventricular septal defect and infundibular pulmonic stenosis with cyanosis. The defects were corrected. A compressed Ivalon patch was used on the septal defect. Potassium arrest was employed. Extracorporeal circulation was for 39 minutes at 48 c.c./Kg./min. The patient remained extremely somnolent for 3 days but recovered completely by the fourth postoperative day.

CASE 4.—D. V. (48-8685), a 12-year-old boy, had a ventricular septal defect and infundibular pulmonic stenosis without cyanosis. The defects were corrected. A Teflon patch was used in the septal defect. Potassium arrest was employed. Extracorporeal circulation was

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for 43 minutes at 52 c.c./Kg./min. On the first postoperative day the patient became irrational, had a left hemiparesis, and left Babinski sign. He recovered completely within 5 days.

CASE 5.—D. W. (55-11755), a 4-year-old girl, had a ventricular septal defect, infundibular and valvular pulmonic stenosis. The defects were corrected through a right ventriculotomy and pulmonary arteriotomy. A Teflon patch was used in the septal defect. Potassium arrest was employed. Extracorporeal circulation lasted 30 minutes at 52 c.c./Kg./min. Coronary air embolus was noted at the end of the pump run but was dispersed by massage. The patient did not awaken and had a right hemiparesis. The temperature rose to 105° F. rectally. She began to have frequent convulsions, mostly on the right side. She was treated with Dilantin and barbiturates but died on the third postoperative day. Autopsy revealed marked edema of the left cerebral hemisphere compatible with cerebral air embolism.

CASE 6.—D. D. (54-4371), a 4-year-old boy, had a large ventricular septal defect which was repaired with a Teflon patch. Anoxic arrest was employed. Extracorporeal circulation lasted 44 minutes at 50 c.c./Kg./min. On the first postoperative day, he had frequent convulsions, coma, and left hemiparesis. He was given digitalis, Dilantin, and barbiturates. Convulsions stopped within 24 hours and at the end of 2 weeks there were no neurologic sequelae.

CASE 7.—S. P. (51-11622), a 9-year-old girl, had a ventricular septal defect with a pulmonary artery pressure of 52/20 mm. Hg. The defect was repaired by direct suture employing potassium arrest. Extracorporeal circulation lasted 27 minutes at 50 c.c./Kg./min. On the first postoperative day the patient became dull, and had a right hemiparesis. She was treated with tracheostomy. On the second and fourth postoperative days, she had convulsions. Complete recovery occurred within 5 days.

CASE 8.—R. R. (55-7620), a 7-year-old boy, had a ventricular septal defect with infundibular and valvular pulmonic stenosis. These were repaired through ventriculotomy and pulmonary arteriotomy. A compressed Ivalon patch was used in the septal defect. Potassium arrest was employed. Extracorporeal circulation lasted 62 minutes at 48 c.c./Kg./min. On the first postoperative day the patient became dull and had a right hemiparesis and bilateral Babinski signs. He was treated with tracheostomy, digitalis, and Dilantin, and completely recovered within 7 days.

CASE 9.—P. P. (58-17082), a 3-year-old girl, had a ventricular septal defect and patent ductus arteriosus with pulmonary artery pressures of 82/34 mm. Hg. The defect was closed with a Teflon patch employing potassium arrest. Extracorporeal circulation lasted 37 minutes at 50 c.c./Kg./min. On the first postoperative day the patient had three convulsions and was semicomatose. She was treated with digitalis, Dilantin, tracheostomy, and barbiturates and completely recovered in 2 days.

CASE 10.—B. H. (57-14109), a 30-year-old woman, had severe infundibular pulmonic stenosis without septal defect. The hypertrophied muscle was excised. Extracorporeal circulation lasted 46 minutes at 46 c.c./Kg./min. On the first postoperative day the patient was somnolent. On the second postoperative day she had right hemiparesis and disported herself in an irrational and rather wanton manner. She completely recovered in 1 week.

Hypothermia.—

CASE 11.—T. S. (43-7186), a 27-year-old woman, underwent repair of an atrial ostium secundum defect. Occlusion lasted 6 minutes and 45 seconds at 29.8° C. Two weeks postoperatively the patient developed a right hemiparesis coincident with episodic atrial fibrillation. The arrhythmia was treated effectively. When next seen 5 months later she had recovered completely.

CASE 12.—D. P. (57-7013), a 17-year-old boy, underwent repair of an atrial ostium secundum defect. Occlusion lasted 6 minutes and 30 seconds at 30° C. On the operative day the patient was difficult to arouse. He had a left Babinski sign. Recovery was gradual and complete within 1 week.

DISCUSSION

The cause of most of these cerebral complications remains obscure. Certainly in two instances (Cases 1 and 11) clot embolism from a suture line can reasonably be blamed. In the remaining hypothermia case (Case 12) and in the instance of the one death (Case 5) air embolism across the defect[5] seems the most obvious factor. This same possibility exists, at least in theory, in the remaining patients, with the exception of B. H. (Case 10) in whom no septal defect existed. It is worth noting that in Cases 8 and 9 the carotid arteries were occluded for 90 seconds at the resumption of normal circulation after cardiac arrest to prevent any air retained in the left ventricle from reaching the brain.

The physiologic implications of extracorporeal circulation have been investigated and well recorded.[1-7] It is improbable that acidosis or hemoglobinemia[1, 2, 6, 7] play important roles in what we have called, for the sake of brevity rather than accuracy, "the pump syndrome." Hypoglycemia[4] as a result of dropping glucose levels in stored blood is hardly a possibility since our heparinized blood is drawn within 2 hours of surgery. The embolization of fibrin clots seems similarly remote as a cause in view of what certainly should be an adequate dose of heparin (1.5 mg. per kilogram of body weight given a few minutes before the vessels are cannulated).

The possible role of antifoam embolization has been investigated[7] and undoubtedly can produce a picture similar to the one just described. We are in no position to compare the amount of antifoam washed into the patient by the pump with the amount needed to produce cerebral findings in experimental animals.

Air embolism can occur in three ways during extracorporeal circulation. (1) Air can be retained in the left side of the heart after the defect is closed, and carried peripherally when normal circulation is resumed. (2) Small air bubbles can enter the systemic circulation from the oxygenator. This would involve passage of the air through the defoaming chamber, the helix and the reservoir, an imposing series of obstacles.[9] (3) The third possibility involves the release of oxygen bubbles from formerly cool blood which becomes warm upon entering the patient.[2, 3]

Interruption of a dominant vertebral artery during the freeing of the subclavian artery, as suggested by Thomas and his associates,[8] is not a probable cause of these complications in view of the fact that the vertebral artery is not ligated and some of the patients here had findings suggestive of right-sided brain damage.

The best possibilities seem to be antifoam embolization and the transmission of air across a septal defect during the repair. Each of these or others may be operative in different patients.

SUMMARY

Twelve patients with cerebral complications following open-heart surgery have been described. Etiological theories have been reviewed.

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TRANSPOSITION OF THE GREAT VESSELS

New Experimental Technique for Its Complete Correction

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COMPLETE transposition of the great arterial trunks is an embryologic defect, the etiology of which is not actually known. In this condition the ascending aorta arises from the right ventricle instead of from the left, and the malplaced pulmonary trunk arises from the left ventricle. Underlying this anomaly is the failure of the tronco-conal ridges to follow their usual spiral course, a clockwise torsion of 180 degrees, as they develop. Radical physiologic changes result and the hold on life of an individual with this pathology is tenuous.

Blalock and Hanlon,[2] in 1950, had tried surgical correction of this anomaly by producing an interauricular defect or a widening of an already existing one. In 1954, Mustard[5] tried a different technique—that of transposing the great arteries by the aid of extracorporeal circulation—while Lillehei and Varco,[4] in 1955, thought of transplanting the superior and inferior venae cavae to the left atrium and the pulmonary veins to the right atrium. Baffes'[1] technique is palliative and does not try to correct the defect but it seems to have produced some favorable results. The only clinical case published in which complete correction of the anomaly was made was by Senning.[8]

Through this paper, I would like to present a new technique in the surgical approach to the problem, an experimental work I have done at the Bailey Thoracic Clinic, attempting to produce complete correction of the anomaly.

METHOD

The experiment was performed on 5 dogs, each weighing about 10 kilograms. For anesthesia, intravenous Pentothal was used. In 1 dog, extracorporeal circulation was used for which the venae cavae were cannulized: the superior vena cava through the right external jugular vein, and the inferior through the right femoral vein. The blood from the venae cavae was drained into a Lucite reservoir which in turn drained into a disc oxygenator of the Kay-Cross type. Oxygenated blood was pumped to the right femoral artery by means of a Hufnagel pump.

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A right thoracotomy was made going through the fifth right intercostal space; a longitudinal incision anterior to the phrenic nerve opened the pericardium. The right atrium was entered through a longitudinal incision starting from the level of the entrance of the superior vena cava and terminating at the level of the entrance of the inferior. The exposed interauricular septum was then incised in a Z-shaped fashion (Fig. 1) to form two flaps: one superior, with a base directed posteriorly, and an inferior, its base located anteriorly. This way, a large artificial interauricular septal defect was produced through which the left atrium was entered and explored. With a "mosquito" forceps, the left auricular appendage was grasped and invaginated into the left atrium (Fig. 2). With atraumatic silk (5-0), the anterior border of the appendage was sutured to the anterior portion of the mitral valve ring, while the posterior border was sutured to the left atrial wall between the posterior portion of the mitral valve ring and the entrance of the inferior pulmonary veins. The sutures were started from the base of the invaginated appendage (Fig. 3).

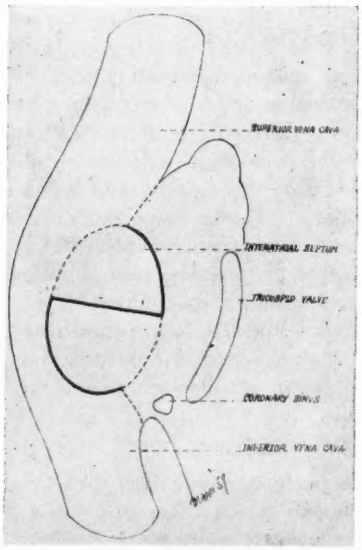

Fig. 1.—Horizontal section of the right atrium at the level of and parallel to the interatrial septum. (Heavy black line in interatrial septum indicates septal incision.)

The tip of the appendage reached the septal defect in such a way that it divided this into two separate openings. The approximating edges of the septal flaps were then sutured to the tip of the appendage, thus dividing the left atrium into two completely separate chambers: a superior into which open the pulmonary veins, and an inferior which is in relation with the mitral valve (Fig. 4).

The next step was to suture the posterior lip of the right atrial wall incision to the free borders of the flaps thereby forming a "tunnel" which connected the venae cavae with the mitral valve through the inferior chamber (Fig. 5).

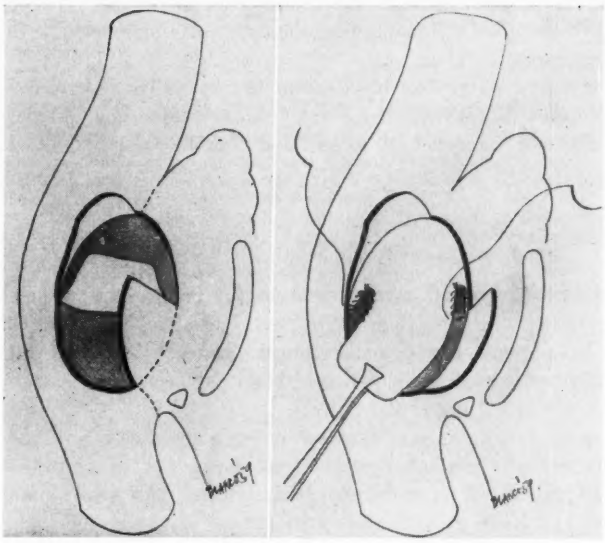

Fig. 2. Fig. 3.

Figs. 2 and 3.—See text. (Heavy black line in interatrial septum indicates septal incision.)

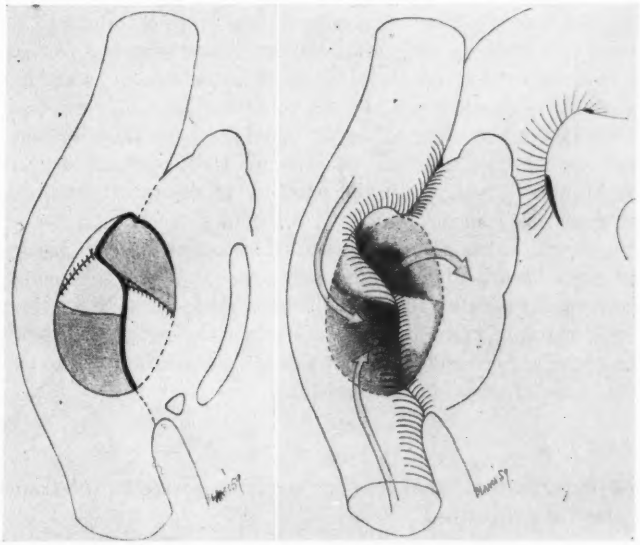

Fig. 4. Fig. 5.

Figs. 4 and 5.—See text. (Heavy black line in interatrial septum in Fig. 4 indicates septal incision.)

To close the rest of the atrium, the anterior lip of the incision was sutured to the wall of the "tunnel." In this manner, the superior chamber came in direct relation with the tricuspid valve.

Thus, the flow of venous blood from the venae cavae was directed to the left ventricle and the oxygenated blood from the pulmonary veins to the right ventricle. Complete physiologic correction was therefore attained.

DISCUSSION

Complete transposition of the great arteries is a relatively frequent congenital anomaly. Abbott[3] discovered 49 cases in a series of 1,000 autopsies of individuals with congenital cardiac pathology. Hanlon and Blalock found 123 cases in medical literature previous to 1948. Campbell[9] estimates that about 8 per cent of his patients with cyanotic congenital heart disease have transposition of the great vessels; in Wood's[7] series of 900 cases, about 1 per cent; in Nadas'[6] cases of 577, about 5.2 per cent.

Because of the increasing interest in cardiac disease and the remarkable progress being made in the surgical correction of both congenital and acquired diseases, this anomaly is more frequently diagnosed. As is obvious, the prognosis is very grave and the great majority of the patients die before 1 year of age. Among the 36 cases of Nadas, only 3 patients survived over a year.

The technique described in this paper is fairly easy and, I believe, can be applied clinically. This procedure would best be carried out with extracorporeal circulation combined with hypothermia in order to have an operative field free of as much blood as possible. The only difficulty which might be encountered is the presence of a large congenital interauricular septal defect, which quite frequently occurs, so that no septal flaps could be made. Although the same procedure could be applied, the absence of septal flaps may produce a certain degree of stenosis in the "tunnel" at the opening of the superior vena cava. In such a case, one can do a modification in which the tip of the left auricular appendage is brought directly over the entrance of the inferior vena cava. This way, blood from the inferior vena cava will flow directly into the left ventricle through the mitral valve. The superior vena cava will be anastomosed end-to-end to the right branch of the pulmonary artery. Hence, oxygenated blood is directed toward the created superior chamber, flows through the interauricular septal defect, tricuspid valve, into the right ventricle, and to the aorta.

In the above experiment, since no actual transposition of the great arteries was present, none of the animals survived.

SUMMARY

A new experimental technique for complete correction of transposition of the great arteries is described.

By producing an interauricular septal defect and by employing an invaginated left auricular appendage, venous blood from the venae cavae is directed toward the left ventricle and to the pulmonary artery while oxygenated blood from the pulmonary veins will flow into the right ventricle and into the aorta.

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STUDIES OF HEALING OF EXPERIMENTAL LEFT VENTRICULAR WOUNDS

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OPERATIVE PROCEDURES involving incisions through the wall of the heart have now become commonplace. The manner of healing of these incisions, therefore, assumes considerable importance, particularly if modifications in surgical technique could be shown to effect favorably the healing process. This report describes the observations made on the healing of left ventricular wounds in dogs.

Only a few other studies of myocardial healing in dogs have been reported. Warren, Blanton, and Muller[4] noted that common to cardiac wounds was some degree of adhesive pericarditis, scarring completely through the myocardium where a clamp was applied, and dense collagen tissue which originated at the site of the wound and extended into the surrounding muscle. A characteristic finding around the silk sutures was a severe chronic inflammatory response with infiltration of lymphocytes, plasma cells, and foreign body giant cells. Carter, and Mac Millan[1] closed left ventricular wounds with mattress sutures and found that 70 per cent of the animals died of wound disruption in 2 to 7 days. Surviving animals were sacrificed at intervals of up to 1 year. The wound edges were held together by a firm narrow scar of fibrous tissue in the early stages. With time, the scar widened and became thin. Sayegh, Harding, and Creech[3] found, in tensile strength studies of myocardial wounds, that the junction of the right ventricular wall and interventricular septum ruptured before the wound.

METHODS

Thirty-one mongrel dogs, weighing from 7.6 to 26.8 kilograms, were used in this study. Wounds were made in the left ventricle in one of two areas. In one group of animals, an area of cyanotic muscle produced by ligation of a large branch of the left anterior descending coronary artery was excised. In the second group, an area of cyanotic muscle produced by ligation of a large branch of the left circumflex coronary artery was removed. The involved area was

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approximated with interrupted mattress sutures of 1-0 chromic catgut swaged on a large curved needle. A continuous suture of silk was then started at one end of the puckered myocardium and, as this was excised, the suture was advanced to prevent leakage of blood. Autopsies were performed at the intervals noted in Table I following this operative procedure. Details of the clinical courses and physiologic studies on these dogs have been reported elsewhere.[2]

RESULTS

The number of animals for each interval and the causes of death are shown in Table I.

TABLE I. INTERVAL AFTER OPERATION OF AUTOPSY ON 31 DOGS

TIME	NUMBER OF DOGS	CAUSE OF DEATH
0 da.	3	Fibrillation
1 da.	1	Atelectasis
2 da.	2	1 atelectasis and 1 unknown
4 da.	4	2 of rupture, 1 atelectasis, 1 empyema
5 da.	2	1 rupture, 1 empyema
7 da.	1	Rupture
8 da.	1	Rupture
10 da.	1	Rupture
12 da.	1	Rupture
14 da.	1	Empyema
15 da.	1	Empyema
4 wk.	1	Sacrificed
8 wk.	1	Aspiration pneumonia
9 wk.	1	Sacrificed
10 wk.	1	Aspiration pneumonia
13 wk.	1	Heart failure
22 wk.	3	Sacrificed
28 wk.	2	Sacrificed
52 wk.	1	Sacrificed
60 wk.	1	Sacrificed
108 wk.	1	Sacrificed

The majority of postoperative deaths was due to rupture of the myocardial wound and occurred between 4 and 12 days after operation. Representative gross specimens at 0, 2, 5, and 7 days after operation are shown in Fig. 1. After a few hours, the myocardial tissue within the suture line became swollen, apparently because of the strangulating effect of the sutures. As a result, the sutures cut into the myocardium. The acute edema then subsided, and the sutures became loose while the contained myocardium appeared increasingly necrotic. By the end of the first week, the affected tissue was a shaggy, friable, necrotic mass. In some animals, two factors afforded protection against wound disruption during this period. The pericardium became adherent and thickened over the wound, or a thin layer of myocardium on the inner aspect of the wound remained viable and healed rapidly. Frequently, both occurred. Histologic study showed the contained muscle to be necrotic and separated from the normal myocardium by a sharp line of demarcation. An acute inflammatory reaction was present at the edge of the necrotic muscle which was still acute at the end of the first week.

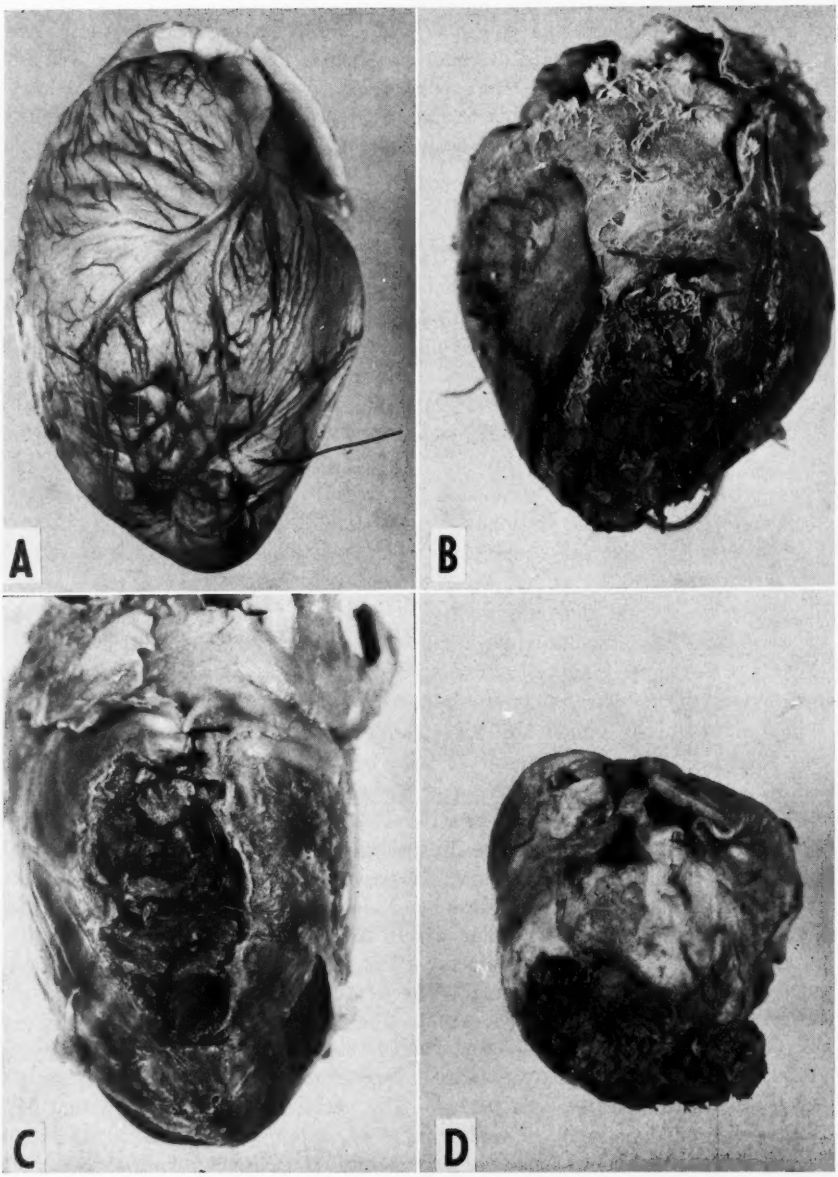

Fig. 1.—The heart shown in *A* is from an animal which died of fibrillation on the day of operation. The wound is edematous, and the suture is cutting into the myocardium. In *B* is shown the loose sutures about the necrotic mass 2 days after operation. *C*, at 5 days, and *D*, at 7 days, show the progression of the necrosis of the affected tissue.

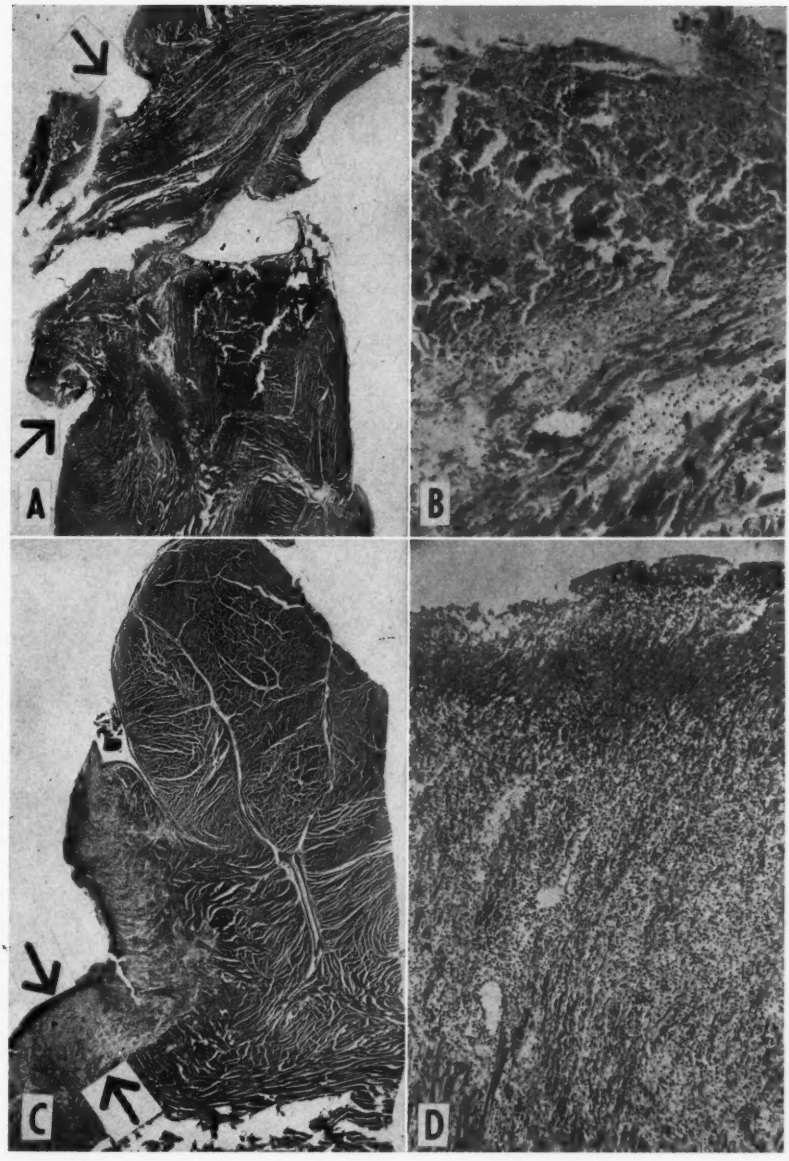

Fig. 2.—In *A* is shown the indentation *(at arrows)* caused by the suture, with bulging of the muscle outward. Necrosis of this muscle seen in *B*. (*A* and *B* are from same animal as that in *B* of Fig. 1, 2 days after operation.) *C* shows the area remaining after slough of the necrotic mass. Dark tissue to the left is a line of dead muscle, the lighter zone *(between arrows)* is the acute inflammatory reaction bordered by normal myocardium. *D* shows the necrotic edge of muscle and the zone of inflammation.

From the eighth through the fifteenth day after operation, 3 of 5 animals died of wound disruption. The necrotic mass of myocardium persisted. The epicardium became thickened, and occasionally the pericardium was adherent and also thick. Some areas of early healing were evident on the endocardial side of the wound. Microscopically, the acute inflammatory reaction persisted, and frequently abscess formation was noted, usually about the suture material. Macrophages, fibroblasts, and loose fibrous tissue now appeared.

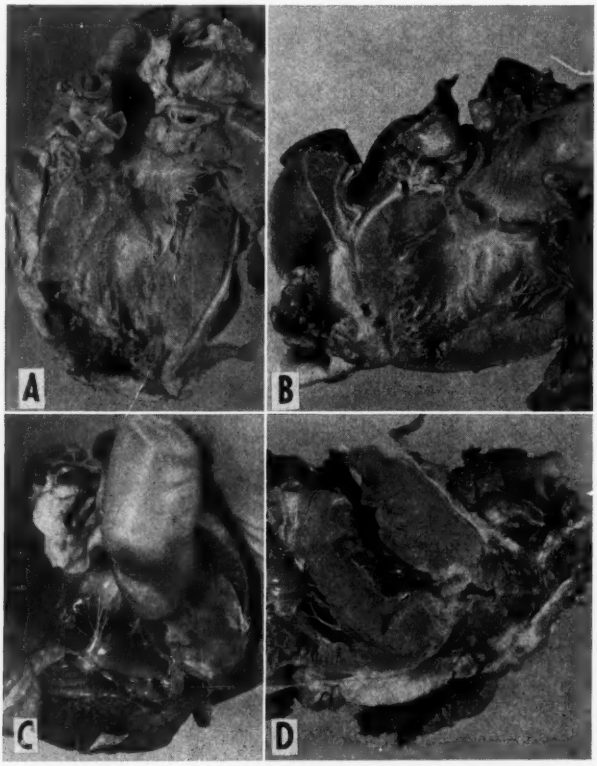

Fig. 3.—*A*, the heart, 2 weeks after operation, shows a thin layer of the inner aspect of myocardium, the pericardium externally after the necrotic tissue has liquified. In *B*, at 8 weeks, the wound is shown to be well organized with thickened pericardium overlying a thin layer of scar in the myocardium. *C*, at 9 weeks, shows the papillary muscle adherent to the area of scar. The outer aspect of the scar was smooth and white and the pericardium thin. In *D*, at 22 weeks, the marked pericardial reaction is evident. The dark area is an abscess around a ball of suture material.

The first animal sacrificed was studied 4 weeks after operation, and the longest period before sacrifice was over 2 years. The major characteristics of the healing process are shown in Figs. 1-6. In some animals, the pericardium remained thin, and the wound in the myocardium followed the usual process of healing. The scar became increasingly dense and in some animals, cartilaginous in areas. In others, the pericardial reaction was intense, occasionally involving the contiguous tissues such as pleura and lung. In all animals, a dominant feature of the healing wound was the persistent reaction about the sutures.

In Fig. 6, the control study of infarction without a surgical wound in the myocardium demonstrates this reaction to suture material and its absence in the infarcted area without suture material.

In those animals sacrificed more than 6 months after operation, the scar in all was thin and translucent, but aneurysm formation was not seen.

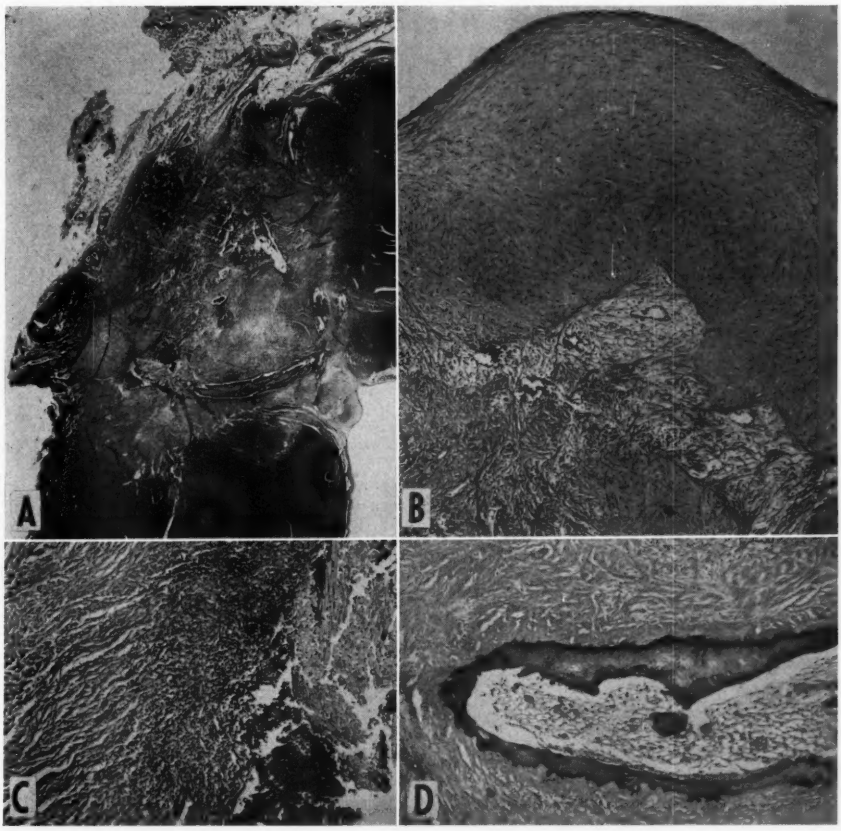

Fig. 4.—*A* and *B*, from heart shown in Fig 3, *C*, at 9 weeks, shows scar extending through myocardium consisting of loose fibrous tissue in some areas and, in others, dense scar which is almost cartilaginous. *C* and *D*, same as Fig. 3, *D*. at 22 weeks, show persistent inflammatory reaction around suture which in one area is present as a rim of cartilaginous tissue which is partly calcified.

DISCUSSION

The persistence of the inflammatory reaction about the suture was the most interesting finding in this study. Two years after operation, this reaction was still present; the cause was not obvious. Although unfortunately the wounds were not cultured at the time of sacrifice of the animals, bacterial stains were made, and no bacteria were seen associated with the inflammatory reaction. The

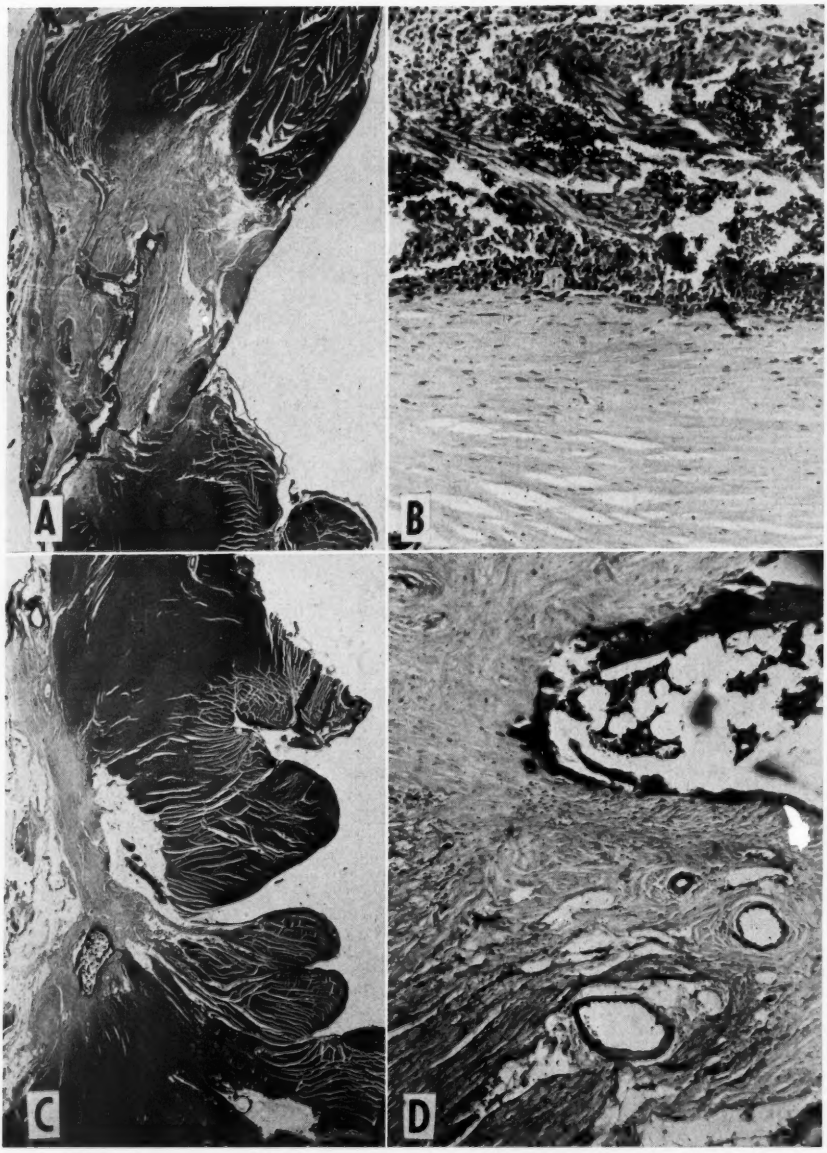

Fig. 5.—*A* and *B* show tissue 52 weeks after operation, *C* and *D*, 108 weeks after operation. A thin scar of dense fibrous tissue is seen, the most striking feature being the persistent reaction about the suture.

same suture in the rectus muscle is firmly encased in mature fibrous tissue without inflammation 2 to 4 weeks after operation, therefore the usual foreign body reaction per se does not seem to be the explanation. It is conceivable that the nearly constant motion of the muscle wall would prolong the reaction to the silk indefinitely. The only other possibility appears to be an abnormal sensitivity of the myocardial tissues to silk sutures, which does not seem very likely.

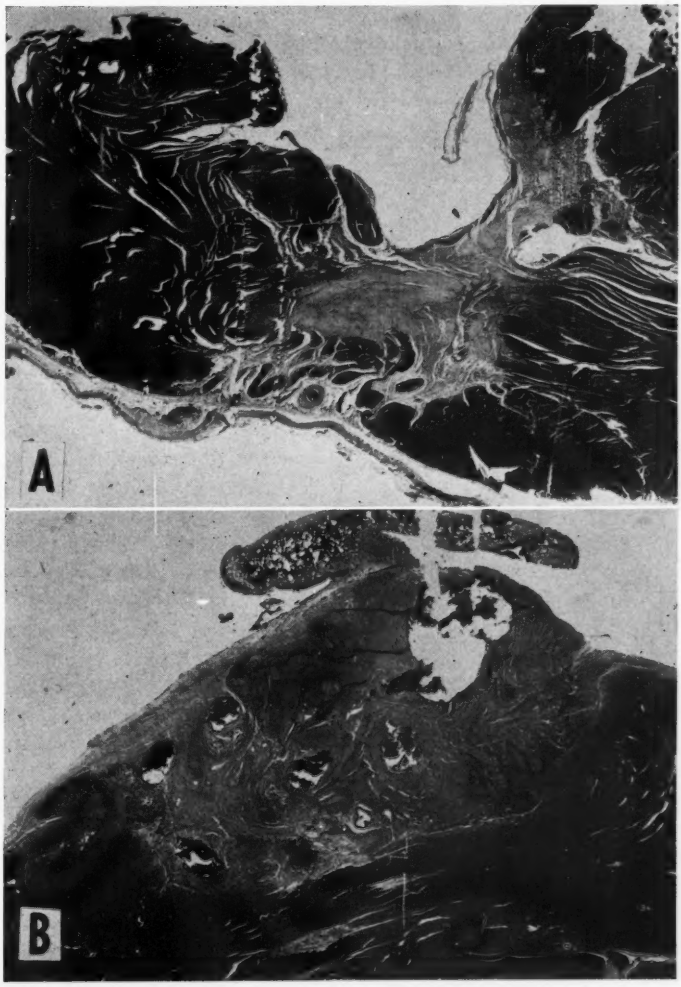

Fig. 6.—Two animals in which infarction was caused by coronary ligation; sacrificed 4 weeks later. In *A*, areas of viable muscle fibers on the epicardial side are seen. No inflammation is present. In *B*, sutures were threaded through the area of infarction, and the scar shows marked acute inflammation about the suture.

Our findings are in agreement with other reported studies with reference to disruption of the myocardial wound and to the thin scar without aneurysm which eventually develops in the survivors.

CONCLUSIONS

1. The use of mattress sutures to approximate left ventricular wounds frequently produces necrosis from tension which results in a high incidence of rupture of the wound.

2. By 4 weeks substantial dense scar tissue is present which continues to mature with time but which results in an area of the ventricular wall which is much thinner than the normal myocardium.

3. An inflammatory reaction about silk suture material within the tissue is present for as long as 27 months.

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A STUDY OF THE MECHANISMS OF CARDIOVASCULAR ADAPTATION TO AN ACUTE VENTRICULAR SEPTAL DEFECT

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THE PHYSICIAN or surgeon who deals with cardiovascular disease may occasionally be confronted with a case of late disruption of the repair of an interventricular septal defect (VSD), or the rare instance of traumatic or post-infarction rupture of a previously intact ventricular septum. The severity of this catastrophe makes a therapeutic approach based on an understanding of the physiologic mechanisms of compensation to an acutely produced defect a rigorous necessity, and has suggested that an examination of these mechanisms might be useful in evaluating the efficacy of some of the measures designed to support the circulation before definitive repair can be undertaken.

The early studies of ventricular septal defects in chronic animals, conducted by Holman and Beck[1, 2] and by Eppinger and Gross,[3] demonstrated a rise in heart rate and an increase in cardiac output with the latter tending to compensate for the flow through the defect.

Subsequent investigations by Frank and his co-workers[4] on peripheral arteriovenous fistulas suggested that when shunt flows are large there is a fall in forward output which can be compensated for by increasing venous return to the heart. This group of investigators also noted that with the initial opening of a peripheral fistula there is a fall in systemic blood pressure followed by an increase in peripheral arteriolar resistance which elevates arterial pressure to near control levels. Sarnoff and his co-workers[5] have noted that peripheral venoconstriction accompanies the elevation of systemic arterial pressure when aortic and carotid baroreceptor hypotension occurs, and that substantial increases in venous tone are associated with increases in pulmonary blood volume. In this connection, Holman's original observations[1, 2] as well as those of Lillehei, Bobb, and Visscher[6] indicated that among the chronic adjustments to experimental interventricular septal defects and arteriovenous fistulas is the gradual increase, even in the absence of cardiac failure, of blood volume, plasma volume, and total body water.

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This set of facts seemed to suggest that not only increases in total blood volume but also its distribution between greater and lesser circulations might be of importance in modifying systemic output in the presence of a central arteriovenous fistula at the ventricular level. It was believed that by increasing peripheral vascular tone with l-norepinephrine, while incrementally changing the total circulating blood volume, thus shifting this blood volume between heart and lungs, and periphery, it might be possible to examine more critically the mechanisms by which the shunt across the interventricular septal defect is controlled.

The same experimental design makes it possible to evaluate the role of transfusion and the efficacy of sympathomimetic agents in the therapy of acute ventricular septal defects.

In the light of the current practice of constricting the main pulmonary artery in the presence of large interventricular septal defects in infancy to protect the pulmonary vasculature from hyperkinetic changes,[7] a small number of experiments were also undertaken to evaluate the role of increasing right ventricular pressure as a compensatory mechanism.

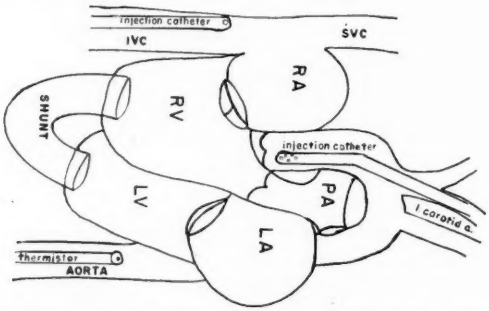

Fig. 1.—Diagram of experimental design. Injection catheters in inferior vena cava at junction of right atrium and at root of aorta. Thermistor in upper abdominal aorta.

METHODS

Dogs, weighing between 18 and 28 kilograms, were anesthetized with 25 mg. per kilogram of pentobarbital sodium (Nembutal). The thorax was opened by a midsternal incision, and respiration was maintained by a positive pressure respirator. After the pericardium was opened, heparin (3 mg./Kg.) was administered intravenously. Supplementary injections of heparin (1 mg./Kg.) were given every hour thereafter.

When exposure of the heart had been completed, an external interventricular shunt was placed from the apex of the left ventricle to the approximate apex of the right ventricle by a modification of the method described by Sarnoff, Donovan, and Case[8] for the introduction of an apical valve in experimental aortic stenosis (Fig. 1). This shunt was composed of a ⅜ inch I.D. Tygon prosthesis which was fitted over a ⅜ inch I.D. stainless steel cannula at each end.

Cardiac output was determined by means of the thermal dilution technique described by Goodyer and his associates.[9] A catheter containing a VECO 32A11 thermistor at its tip was placed in the upper abdominal aorta via the right femoral artery. Measurement of total cardiac output was provided by the injection of a standard bolus of iced saline introduced rapidly from a calibrated syringe through a 100 cm. No. 8 Cournand catheter directly into

the right atrium at its junction with the inferior vena cava (IVC). The shunt was of sufficient length so that in all instances an adequate downslope of the dilution curve could be obtained before recirculation occurred. Measurement of systemic output was provided by the injection of a proportionately smaller bolus of iced saline introduced through a No. 8 Cournand catheter, which was inserted via the left carotid artery, directly into the root of the ascending aorta just above the sinuses of Valsalva. This catheter was specially modified so as to permit only radial ejection of the bolus. The work of Peterson and coworkers[10] indicates that the mixing jet of aortic ejection provides sufficient turbulence to assure complete and even dilution of the injectate in aortic blood. Comparison of outputs done by successive injection at the two different sites, when the shunt was closed, demonstrated agreement within ±9 per cent. Immediately repeated outputs done from the same site during a given steady state agreed within ±4 per cent.

Catheters of No. PE 205 or No. PE 240 polyethylene were placed in the aorta via the left femoral artery, and directly into the right ventricle and main pulmonary artery. These catheters were connected to Hathaway strain gauges, and continuous arterial, pulmonary arterial, and right ventricular pressures were recorded, as were the thermistor dilution curves, on Sanborn direct writing equipment. In nine of the experiments, mean left and right atrial pressures were measured by saline manometers. The position of all catheters was checked at post mortem.

Prior to the initiation of experimental observations, the measured operative blood loss was replaced. During the experimental period, one or more pairs of successive inferior vena caval and aortic injections were performed with the shunt closed. These determinations were used as base line controls for comparison with similar pairs of successive total and systemic outputs obtained when a steady state had been achieved after the shunt was opened, at the same blood volume increment. The shunt was then closed, the animal's blood volume increased by another increment, and control and open-shunt outputs were measured in this manner until the study was terminated. A minimum of 2 and usually 4 minutes of unchanged arterial blood pressure and heart rate was allowed to elapse after any changes in equilibrium before outputs were measured. Successive total and aortic outputs were never more than 2 minutes apart, and were often measured within a minute of each other; the interval between determinations depending on the length of time required for the thermal dilution curve to return to the baseline; the duration being longer when shunting produced recirculation. Repeat cardiac outputs were measured whenever the length of time between paired determinations appeared to be excessive, or if there was any question of changing parameters.

In those experiments in which the action of l-norepinephrine was studied, this sympathomimetic agent was administered by constant infusion into the inferior vena cava.

In those studies in which the effects of increasing right ventricular pressure alone were examined, the main pulmonary artery was constricted by means of a Rumel tourniquet in such a manner that the same degree of stenosis could be reproducibly achieved.

Shunt flow was calculated by the subtraction of systemic flow from total cardiac output.

Total peripheral resistance was calculated in arbitrary units by dividing mean arterial pressure in millimeters of mercury by systemic output in liters per minute.

The resistance presented by the right ventricle to shunted flow was calculated by dividing mean right ventricular systolic pressure in millimeters of mercury by shunt flow in liters per minute. This calculation is not intended to be a measure of shunt resistance, since the shunt is external; it is rather intended as an index of the resistance imposed by the right ventricle to the flow of blood from the right ventricular shunt orifice.

Pulmonary vascular resistance was calculated in arbitrary units by dividing:

$$\frac{\text{Mean pulmonary artery pressure in cm.H}_2\text{O} - \text{Mean LA pressure in cm.H}_2\text{O}}{\text{Pulmonary artery flow in liters per minute}}$$

Central blood volume was obtained from the inferior vena caval dilution curve by the formula:

$$\frac{\text{Mean circulation time (sec.)} \times \text{cardiac output (ml./min.)}}{60 \text{ (sec./min.)}}$$

Right and left ventricular minute work (RVMW, LVMW) in grammeters were calculated by multiplying:

Mean right ventricular systolic pressure, or mean aortic pressure in cm.H_2O, by total cardiac output in liters per minute.

Right ventricular mean systolic pressure rather than mean pulmonary artery pressure was chosen for the calculation of right ventricular minute work so that meaningful comparisons could be made between right ventricular work in the control state and in those instances in which relative or absolute pulmonary stenosis was present.

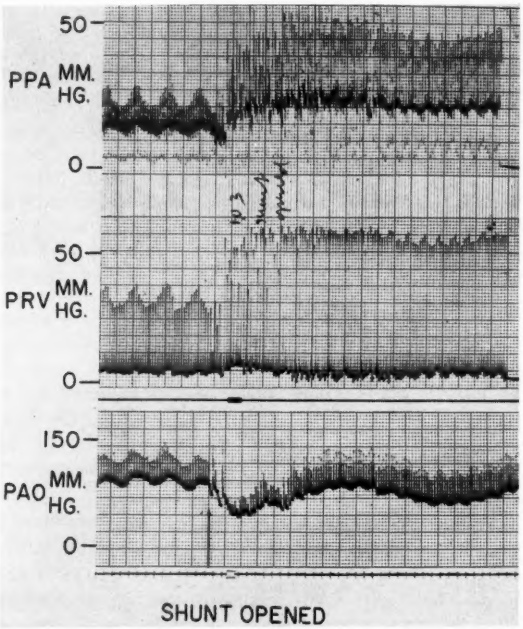

Fig. 2.—Record of opening of interventricular shunt. *PA*, aortic pressure; *PRV*, right ventricular pressure; *PPA*, pulmonary artery pressure. Note arrythmia preceding increase in rate. Widening of pulse pressure as well as strenuous effort at respiration occurs following opening of interventricular shunt.

RESULTS

The material reported in this paper comprises the data obtained from 14 successful experiments containing a total of over 160 pairs of outputs.

Fig. 2 is a record of the alterations in pressure which occur when the experimental ventricular septal defect is opened. There is an immediate fall in aortic pressure which is accompanied by a pari passu rise in right ventricular pressure and pulmonary artery pressure to higher levels. As arterial pressure tends to recover, although mean pressure usually declines somewhat from the control level, there is, following an initial slowing, an increase in the rate and often a widening of the pulse pressure. The right ventricular systolic pressure tends to be maintained at a higher level. Right ventricular diastolic

pressure, on the other hand, after an initial elevation lasting a few beats, then falls to a level which is lower than control so that the pulse pressure is widened. Pulmonary artery pressure also follows this pattern. In some instances, evidence of an apparent sinus arrythmia (from pressure pulse tracings alone) is present during the period associated with the increase in heart rate, although the work of Ferguson[11] and of Coleridge and Linden[12] seems to indicate that the presence of sinus arrythmia is not necessary for the initiation of cardiac acceleration in the initial period following the opening of an arteriovenous fistula. During the initial period of circulatory adjustment, the animal often makes strenuous efforts at respiration even though on a respirator. This phenomenon has been commented on previously in relation to the sudden opening of peripheral arteriovenous fistulas by Nickerson and his co-workers[13] and Coleridge and Linden.[12]

Fig. 3 is the plot of an experiment in which an experimental interventricular septal defect was produced allowing a shunt flow equal to 160 per cent of the initial control cardiac output with a total output increase to 234 per cent of control. After control and experimental points were taken, the animal was then infused with blood in increments of approximately 6 per cent of its blood volume (calculated on the basis of 9 per cent of body weight) given slowly over a 10 to 15 minute period. After stabilization of vital signs had occurred, new control and experimental output determinations were made.

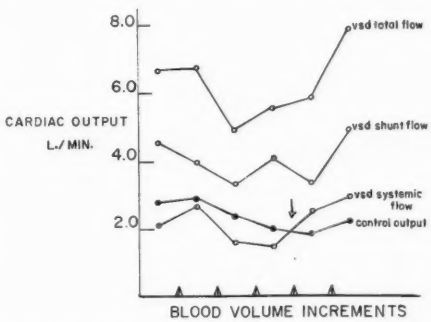

Fig. 3.—The role of blood volume in assisting compensation to an acute VSD. 27 Kg. dog. Total blood volume increased by increments of 6 per cent. Control cardiac output shown by *closed circles*. VSD values shown by *open circles*. Point of "changeover" designated by *arrow*.

The most striking observation is that when the animal's blood volume was increased by approximately 25 per cent of the calculated initial level, there was a reversal of the drop in systemic flow which occurs when the interventricular shunt is opened. This "changeover" occurred in all animals studied in this manner. The point of reversal occurred after an increase in blood volume of between 23 and 36 per cent with an average of 29 per cent and was maintained with further increments of blood loading. That this reversal is not necessarily due to an increase in total cardiac output caused by blood loading but rather to a change in the proportion of blood shunted, and that it may be associated with a decrease in total cardiac output, is shown in Fig. 4. Here an initial shunt flow which was 409 per cent of the control cardiac output, representing an increase in pulmonary flow to 519 per cent of control levels, decreased on blood loading so that at the time of "changeover" the pulmonary artery flow was only 45 per cent of the pulmonary artery flow in the normovolemic state with the ventricular shunt patent. The ratio of systemic flow divided by shunted flow, however, increased from *0.268* prior to "changeover" to *0.366* when this reversal occurred. The mean of the four systemic flow to shunt flow ratios prior to "changeover" was *0.329* compared to the mean of *0.577* for the four points after this phenomenon had occurred. In all animals studied, regardless of total output, the ratio of systemic flow to shunt flow increased when systemic flow, with the shunt patent, exceeded the control cardiac output.

The effect of l-norepinephrine (Levophed) in modifying the basic response to blood loading is quite interesting. When this sympathomimetic drug was administered with the shunt open, in the presence of a normal or slightly reduced blood volume, there was a further decrease in forward output, and also a marked decline in total output and shunted flow. As blood infusion progresses, however, there is a reversal of this tendency. As volume increases, the administration of l-norepinephrine in the presence of an open shunt produces an increase in systemic flow compared to the systemic flow of the ventricular septal defect at the same volume level but without vasopressor. Fig. 5 shows a plot of the ratio of VSD systemic flow/control output, with and without infusion of l-norepinephrine.

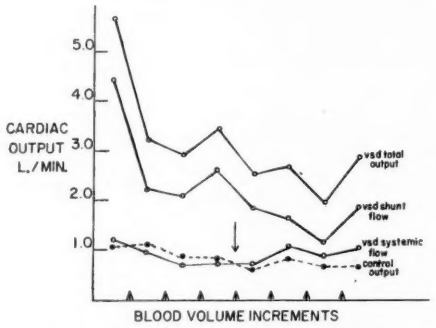

Fig. 4.—Blood volume increments producing compensation to an acute VSD with a reduction in pulmonary flow. 19 Kg. dog. Total blood volume increased by increments of 9 per cent. Control cardiac output shown by *closed circles*. VSD values shown by *open circles*. Point of "changeover" designated by *arrow*.

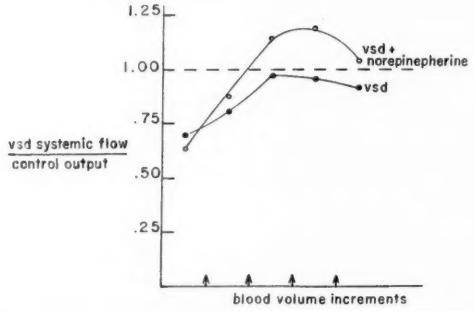

Fig. 5.—Potentiation of blood volume increase by norepinephrine. 28 Kg. dog. Ratio of $\frac{\text{VSD systemic flow}}{\text{control output}}$ with and without 1.3μg/Kg./min infusion of l-norepinephrine. Total blood volume increased by increments of 8 per cent.

It demonstrates that as blood volume is increased by increments of 8 per cent, l-norepinephrine potentiates the blood loading with regard to its salutory effects on forward flow.

Fig. 6, showing the ratio of VSD systemic flow/control output in the presence of two concentrations of l-norepinephrine, demonstrates that in the hypovolemic or normovolemic condition, the depressing effect of a ventricular septal defect on body flow is directly related to the concentration of the sympathomimetic. This effect is decreased proportionately by adding volume. When blood volume is elevated l-norepinephrine increases systemic flow again proportionately to concentration. The higher concentration infusion increases systemic flow to 135 per cent of control, the lower concentration infusion elevates it to only 99 per cent of control; but both are significantly higher than the case in which no l-norepinephrine was used.

Changes in Central Volume.—The observation that l-norepinephrine potentiates the beneficial effects of blood loading on forward output when blood volumes are high, and yet depresses forward output when blood volume is low or normal, suggests that the partition of total volume between heart and lesser circulation and the periphery is an important factor in establishing compensation to the ventricular shunt. This speculation would appear to be supported by the information presented in Fig. 7. This graph, which represents the same experiment previously shown by Fig. 5, demonstrates the increase in central blood volume compared to control in the presence of a ventricular septal defect, both with and without l-norepinephrine, as total blood volume is increased. There are

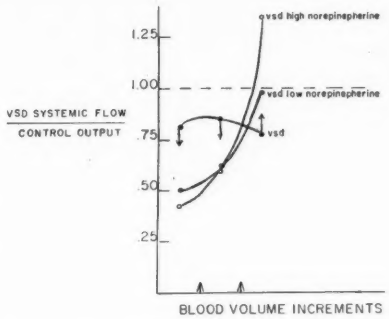

Fig. 6.—Effect of two concentrations of l-norepinephrine on the potentiation of blood volume increments. 23 Kg. dog. Ratio of $\frac{\text{VSD systemic flow}}{\text{control output}}$ in the presence of 0.9μg/Kg./min., and 1.6μg/Kg./min. l-norepinephrine, and without vasopressor. Operative blood loss of approximately 200 c.c. not replaced in order that animal be initially hypovolemic. Total blood volume increased by increments of 10 per cent.

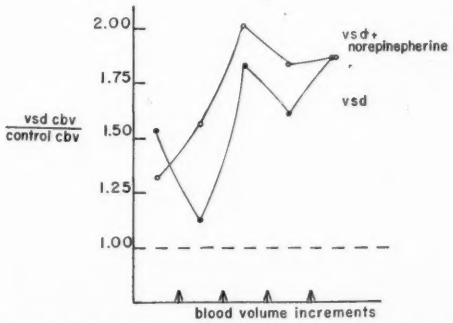

Fig. 7.—Potentiation of increase in central blood volume by l-norepinephrine. 28 Kg. dog. Ratio $\frac{\text{VSD central blood volume}}{\text{control central volume}}$ with and without 1.3μg/Kg./min. infusion of l-norepinephrine. Total blood volume increased by increments of 8 per cent. Experiment identical with that shown in Fig. 5.

several points of significance in relation to this figure. First, the central volume is greater than control whenever the ventricular shunt is open. Second, the effect of l-norepinephrine in elevating the VSD systemic flow/control output ratio is paralleled by increases in central blood volume. Third, as total volume is increased, the central volumes, with and without l-norepinephrine, tend to approach a common value. This may indicate perhaps that the limiting capacity of the central reservoir has been reached, or that the ability of the left heart to handle this excessive volume has been exceeded. However, the mean left atrial pressure at the point of coincidence was only 15.5 and 15.4 cm.H_2O for the

ventricular shunt with and without l-norepinephrine, respectively. It is interesting to note that central volume is higher in the untreated ventricular septal defect before the first increment of volume is added, and then falls after the initial blood loading. This may possibly be explained by the supposition that at low peripheral blood volumes certain vascular beds are not perfused at all as their critical closing pressure is not exceeded; but when peripheral volume increases to the point where their critical closing pressure is exceeded, the volume which they accept may be considerably larger than the added increment, thus causing a decrease in central volume in compensation.

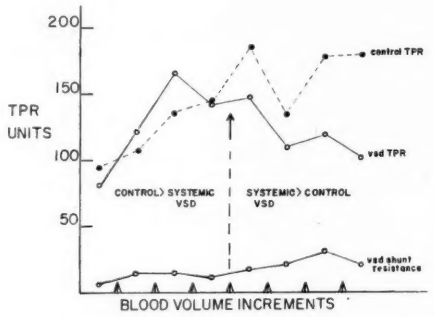

Fig. 8.—Changes in total peripheral resistance and shunt resistance in response to blood volume increments. 19 Kg. dog. Total blood volume increased by increments of 9 per cent. Control TPR shown by *closed circles*. VSD TPR, and shunt resistance shown by *open circles*. Point of "changeover" designated by *arrow*. Experiment identical with that shown in Fig. 4.

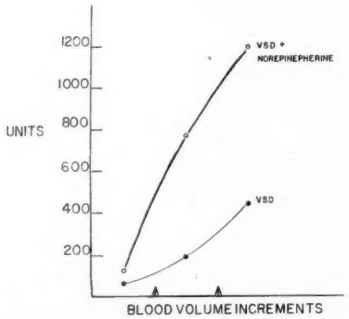

Fig. 9.—Increase in shunt resistance by l-norepinephrine. 27 Kg. dog. The effect of a 1.4μ/Kg./min. infusion of l-norepinephrine on the resistance presented by the right ventricle to shunted flow. Total blood volume increased by increments of 8 per cent.

Changes in Resistance to Left Ventricular Ejection.—When the interventricular shunt was open, total peripheral resistance increased over control values at any level of total blood volume at which forward flow was less than control output. This occurred regardless of whether the equilibrated mean arterial pressure was higher, lower, or the same as control values. On the other hand, the resistance presented by the right ventricle to shunted flow rises with increments in blood volume (Fig. 8).

The effect of l-norepinephrine on peripheral resistance is much as might be expected. At low or normal blood volumes, the arteriolar resistance of the ventricular shunted animal is elevated by the vasopressor. With increases in blood volume, the arteriolar resistance with l-norepinephrine falls as body flow increases, at a time when the resistance of the

control and the untreated ventricular septal defect are still elevated. The resistance presented by the right ventricle to shunted flow is in general elevated by l-norepinephrine at any increment in blood volume (Fig. 9).

Changes in Pulmonary Resistance.—Fig. 10, *A* demonstrates that, at any given pulmonary artery flow, pulmonary resistance is higher in the VSD in which l-norepinephrine is being infused than in the case in which this vascular bed has not been exposed to the sympathomimetic agent. Both instances, however, show resistance increases over the control flows. In order to ascertain whether these resistance increases were due to pulmonary vasoconstriction, or whether the increased control blood volume had merely shifted the pressure volume curves of the pulmonary vasculature to a steep portion of the curve, changes in pulmonary resistance were plotted against increases in central blood volume (Fig. 10, *B*). This set of curves shows a pattern similar to those for flow and demonstrates that, at the same central volume, pulmonary resistance is higher with l-norepinephrine than without it. This suggests that in addition to the previously demonstrated central volume changes there probably are increases in pulmonary vascular tone in the presence of a patent ventricular septal defect and that these increases are further potentiated by l-norepinephrine.

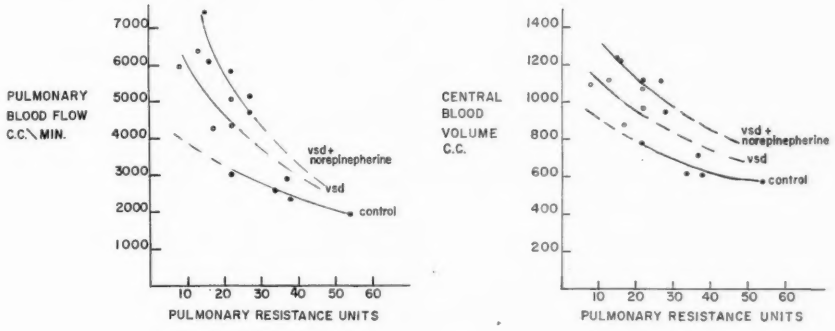

Fig. 10.—*A*, Changes in pulmonary vascular resistance I. 28 Kg. dog. The relation of pulmonary vascular resistance to pulmonary blood flow in the control state *(closed circles)*, VSD *(open circles)*, and in the VSD with a 1.3a/Kg./min. infusion of l-norepinephrine *(half-closed circles)*.

B, Changes in pulmonary vascular resistance II. Same as 10,*A*. The relation of pulmonary vascular resistance to central blood volume in the control state *(closed circles)*, VSD *(open circles)*, and in the VSD with a 1.3a/Kg./min. infusion of l-norepinephrine *(half-closed circles)*.

Changes in the Work of the Two Ventricles.—For any given increase in cardiac output in the presence of a patent interventricular shunt there is a disproportionate increase in the minute work of the right ventricle compared with that of the left. Viewed in another way (Fig. 11), as increments in blood volume are added to the animal, the ratio of $\frac{\text{RVMW}}{\text{LVMW}}$ with the shunt open is greater at every point compared with control values, although both ratios tend to increase slightly. In general, the ratio of the work of the two ventricles approaches a plateau as the systemic flow, with the shunt patent, becomes greater than control cardiac output (Fig. 12). In other words, per cent change in right ventricular work is greater than the per cent change in left ventricular work as resistance to the shunt tends to become greater (Fig. 8).

L-norepinephrine increases the absolute minute work of both right and left ventricles in the presence of a ventricular shunt. The ratio of $\frac{\text{RVMW}}{\text{LVMW}}$ is either unchanged or slightly increased over the untreated VSD.

Changes in Ventricular Function.—While no definitive attempt was made to do ventricular function curves, it was possible, by plotting the data obtained, to gain some information as to the direction of change in this important parameter in the presence of a patent ventricular shunt. Fig. 13 presents the data plotted as increasing right ventricular stroke work against right ventricular filling pressure (as reflected in mean right auricular pressure). Although the points are few, it is quite obvious that a shift of considerable magnitude to a more efficient ventricular function curve has occurred as a result of opening the interventricular fistula. This "shift to the left" is further exaggerated by infusion of l-norepinephrine.

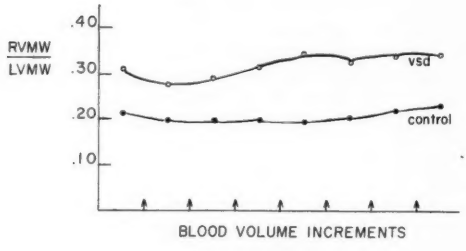

Fig. 11.

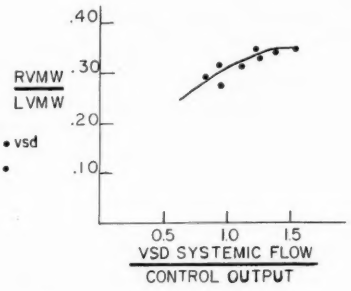

Fig. 12.

Fig. 11.—Ratio of the work of the two ventricles as total blood volume is increased. 19 Kg. dog. Total blood volume increased by increments of 9 per cent. Experiment identical with that shown in Fig. 4.

Fig. 12.—Change in ratio of the work of the two ventricles as VSD systemic flow becomes greater than control output. Experiment identical with that shown in Fig. 4.

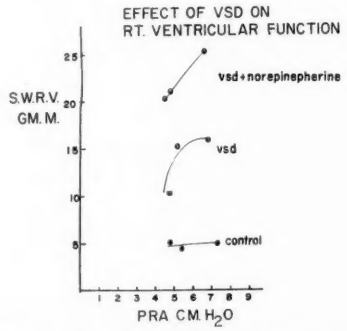

Fig. 13.—Effect of interventricular shunt on right ventricular function.

Changes in Right Ventricular Pressure Independent of Pulmonary Resistance.—Finally, it was considered worth while to examine the situation in which a constricting tape was placed around the main pulmonary artery so as to limit egress from the right ventricle, and thus increase right ventricular pressure independently of pulmonary vascular resistance. This maneuver assumes some importance in view of the popularity of the Dammann-Muller procedure in the preliminary therapy of infants presenting with large interventricular septal defects and without pulmonary stenosis who get into difficulty at a time of life when definitive operative procedures are hazardous.

Although the number of experiments performed was limited to 2 animals, it is considered worth while to present these data for purposes of comparison.

When the tape surrounding the main pulmonary artery is partially occluded, in the presence of an already patent ventricular septal defect, there is an immediate rise in right

ventricular systolic pressure. The diastolic pressure of the right ventricle usually rises as well, but may subsequently fall. The magnitude of this change may be quite remarkable rising from 50/0 to 70/10 mm. Hg with only a modest maintained decrease in pulmonary artery pressure from 43/10 to 38/10 mm. Hg. In order to produce a sustained fall in pulmonary artery pressure to near normal levels, it was necessary to constrict the pulmonary artery ligature to the point at which right ventricular pressure approached systemic levels, namely 105/0 mm. Hg, with a systemic pressure of 110/70 mm. Hg (Fig. 14). Iatrogenic stenosis of the pulmonary artery caused a reduction in the absolute magnitude of pulmonary artery flow and in the quantity of blood shunted. Although under conditions of blood infusion, the

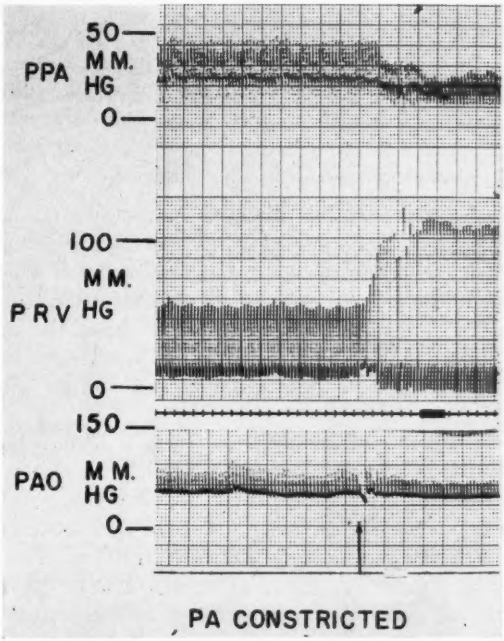

Fig. 14.—Record of constriction of the pulmonary artery in the presence of an interventricular shunt. *PAO*, aortic pressure; *PRV*, right ventricular pressure; *PPA*, pulmonary artery pressure.

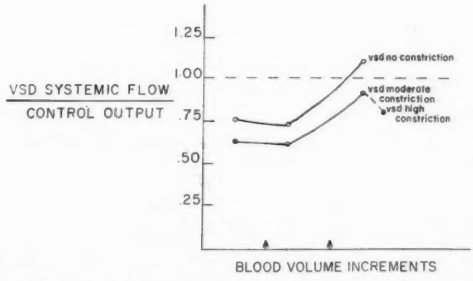

Fig. 15.—Effect of pulmonary artery constriction on the compensation to an acute VSD. 19 Kg. dog. Ratio $\frac{\text{VSD systemic flow}}{\text{Control output}}$ with and without pulmonary artery constriction as blood volume increased by increments of 11 per cent.

per cent of total output shunted may actually increase. However, pulmonary artery constriction under these conditions caused a decrease in the VSD systemic flow/control output ratio which is always greater than that present in the uncomplicated interventricular shunt (Fig. 15). On partially occluding the pulmonary artery, arterial pressure either remained unchanged or rose slightly toward control levels.

The proportion of right ventricular work was increased by constriction of the pulmonary artery so that the $\frac{\text{RVMW}}{\text{LVMW}}$ ratio was increased. The reduction in pulmonary artery flow consequent to moderate constriction (which was insufficient to lower materially pulmcnary artery pressure) often resulted in an absolute reduction in right venticular minute work. Nevertheless, in these acute preparations, pulmonary artery constriction of sufficient degree to significantly reduce pulmonary artery pressure was associated with a marked rise in right ventricular minute work, even though total pulmonary flow was reduced.

The resistance presented by the right ventricle to shunted flow was, of course, increased by pulmonary artery constriction and was qualitatively proportionate to the degree of constriction.

DISCUSSION

The compensatory mechanisms involved in the adaptation of the cardiovascular system to an acutely produced interventricular shunt appear to be directed toward the maintenance of an adequate systemic blood flow and arterial pressure, and toward an increase in cardiac contractility by which to handle the increased work load suddenly placed upon the myocardium. It seems logical to assume that an understanding of these mechanisms, their origin, interrelation, and limitations is essential for a rational approach to the therapy of this difficult problem.

The studies of Frank and others[4, 11] led them to believe that in peripheral arteriovenous fistulas, the factor limiting an increase in systemic output is the volume of blood available for venous return. The investigations reported in this paper would appear to extend the general sense of these observations to include very large fistulas directly connecting the two ventricles. There are, nevertheless, certain important reservations. In peripheral shunts, the increased cardiac output tends to equal, or at least approach, the control output plus the fistula flow. The increased minute venous return is responsible for the increase in pulmonary flow, and increases in blood volume assist compensation by enabling further increases in cardiac output so that systemic output is maintained by increasing total cardiac output. A significant reduction in the shunt flow occurs only in the presence of frank right-sided failure. However, in interventricular fistulas, the increase in total cardiac output may be very great, but in the uncompensated state seldom equals the control cardiac output plus the shunted flow, resulting in an inevitable decrease in forward output. Compensation is associated with a dynamic shift of blood volume into the cardiopulmonary area and is achieved by a combination of mechanisms whose net effect is to decrease the proportion of shunted flow, and may result in an actual decrease in total cardiac output at the same time as forward output is increasing over control levels. Increases in blood volume potentiate compensation by increasing the volume of blood shifted centrally, although the minute volume returned to the right heart may remain the same or even decrease in the presence of an acute

defect. The fact that the volume of blood required to effect an increase in systemic output which exceeds control values approximates the increase in blood volume, noted by Holman and Beck[1] in chronic animals which had achieved evidence of compensation, appears to lend support to the hypothesis that hypervolemia is a protective measure rather than a decompensatory consequence.

The increased pulmonary vascular resistance operates qualitatively in the same direction as the increase in central blood volume. Both effects tend to increase the resistance presented by the right ventricle to shunt flow by increasing right ventricular systolic pressure at the expense of disproportionately increasing right ventricular minute work. It is here that the demonstrated ability of the right ventricle to compensate by moving to a more efficient member of its family of Starling curves[14] assumes considerable importance, since this enables it to do an increased quantity of work from the same filling pressure. This improved myocardial contractility is further evidence that the increased resistance to shunted flow is associated with cardiac compensation rather than cardiac failure. This observation of a shift to a more efficient ventricular function curve in the presence of a patent ventricular septal defect is compatible with the work of Wegria and co-workers[15] and Glaviano and Nykiel[16] who studied myocardial oxygen consumption in the presence of a peripheral arteriovenous fistula and demonstrated evidence of increased myocardial efficiency. It is also supported by the pressure pulse studies of Dillon and Schreiber[17] which led them to believe that in acute interventricular septal defects the right ventricle was creating "more pressure energy during systole," and which they felt was secondary to increased diastolic distention. However, in 7 of their 18 experiments no change in "initial tension" (presumably end diastolic pressure) occurred, although the right ventricle was obviously doing more work.

The actions of l-norepinephrine as a cardiovascular sympathomimetic agent have been carefully studied by many groups. The increase in peripheral arteriolar resistance has been reported by Goldenberg and associates,[18] Barcroft and Swan,[19] and by Brewster, Isaacs, and Andersen.[20] Its action as a venoconstrictor has also been noted by Barcroft and Swan[19] and the important consequences of this venoconstriction in terms of increasing central blood volume have been reported by Rashkind and co-workers[21] and also by Rose and Fries.[22] The cardiopulmonary location of this increase has been further evidenced by the work of Shadle, Moore, and Billig.[23] The changes effected by l-norepinephrine on the pulmonary vascular resistance are less clearly defined. Regan and colleagues,[24] however, reported an increase in pulmonary arteriolar resistance in normal subjects, although not in patients with valvular insufficiency on the left side of the heart. The role of l-norepinephrine in increasing myocardial contractility and chronicity are also well known.[14, 25] The recent experiments of Brockman and co-workers[26] emphasize that the inotropic effects of direct and reflex cardiac sympathetic nerve stimulation can be mimicked with l-norepinephrine.

In the light of these facts it is perhaps possible to explain the biphasic role of l-norepinephrine in modifying the response to blood infusion in the presence

of a ventricular shunt. At normal or slightly reduced blood volumes, the relative effect of increased arteriolar resistance is probably more important than the small additional quantity of venous return mobilized by the enhanced venoconstriction. The net result is an increase in the proportion of shunt flow and a decrease in forward output which further reduces venous return, and which may at times be sufficient to reduce total pulmonary flow. With increasing blood volumes, the effect of the sympathomimetic agent in increasing the quantity of blood mobilized centrally by venoconstriction would appear to outweigh the effect of increased peripheral arteriolar resistance so that the net effect is an increased resistance to shunt flow. In addition to the effect induced by the redistribution of blood volume, there is also evidence of a shift in pulmonary vascular resistance to a higher curve. Whether this represents a true active vasoconstriction produced by the l-norepinephrine or merely the effects of increased bronchial arteriolar pressure cannot be determined from these experiments. Nevertheless, for a given increment in total blood volume, the ratio of VSD systemic flow to the control cardiac output approaches unity more rapidly with l-norepinephrine than without it, and this increase in forward output is paralleled by an increase in central blood volume.

Another aspect of the use of l-norepinephrine in the presence of a patent interventricular shunt is that the minute work of both ventricles is increased as is, in general, the proportion of this work handled by the right ventricle. Although the efficiency of myocardial contractility is also increased, it remains to be demonstrated whether the increased demands placed upon the heart are sufficiently requited by the compensatory measures which are induced by the action of this sympathomimetic agent.

The results of the Dammann-Muller procedure, in this preparation, are also quite interesting, in that they demonstrate that although constriction of the pulmonary artery reduces shunted as well as total pulmonary flow, it is at the cost of a concomitant decrease in systemic output, as well as a disproportionate increase in right ventricular work. Of additional importance is the observation that even without right ventricular hypertrophy, and with an essentially normal pulmonary vasculature, pulmonary artery constriction must be taken to a degree which will produce marked right ventricular hypertension before pulmonary artery pressure returns to normal. It is probable, however, that the right ventricle is better able to compensate for an increased pressure load than are the pulmonary arterioles.

Having considered the mechanisms involved in the cardiovascular compensation to acute interventricular septal defect, as well as their modification by a sympathomimetic agent, it would appear to be worth while to examine the physiologic pattern which they present in terms of their possible organization. The first set of observations recorded in this paper note that when the abnormal connection between the ventricles is opened, there is an initial sharp reduction in mean arterial blood pressure as well as in pulse amplitude, and presumably also a fall in forward output. As equilibrium is re-established there appears an increase in rate, a tendency for mean arterial pressure to return to control

levels, usually a widening of pulse pressure, and a marked increase in pulmonary artery flow although systemic output seldom equals the control level. Associated with these events, there is a significant increase in peripheral resistance, an apparent rise in pulmonary vascular resistance, and there may be evidence of an important increase in venomotor tone as denoted by the redistribution of blood volume between greater and lesser circulations. At the same time, there is a marked shift of ventricular function to a more efficient curve.

All of these changing parameters have a common denominator. All are capable of being reflexly affected by the unbalancing of a single regulatory system, and one which is demonstrably altered by the initial systemic hypotension; namely, the carotid sinus and aortic baroreceptors.

Evidence that the increase in peripheral resistance is suggestive of an active peripheral arteriolar vasoconstriction is provided by the fact that after the initial fall, when the ventricular shunt was opened, the arterial blood pressure tended to return to control levels even though systemic flow had decreased. The original observations of Koch[27] as well as those of Heymans and others[28, 29, 30] demonstrated a rise in arterial blood pressure with carotid baroreceptor hypotension. Gilmore and Siegel[31] have data which demonstrate a marked increase in peripheral arteriolar resistance over a wide range of systemic flows under the same circumstances.

Although the work of Coleridge and Linden[12] strongly suggests that the increase in heart rate and cardiac output in the presence of a peripheral arteriovenous fistula is primarily due to an increase in venous return to the heart rather than to the reflex effects of the sudden lowering of arterial pressure; nevertheless, the reflex effects of baroreceptor hypotension in producing tachycardia as shown by Heymans[32] must play some role. Furthermore, Billig and Shadle[33] have brilliantly demonstrated that the reflex bradycardia, attendant on closure of systemic arteriovenous fistulas, is dependent on the integrity of carotid sinus and aortic baroreceptors. Glaviano[34] has demonstrated that the heart rate changes induced by opening an arteriovenous fistula are mediated by vagal efferent fibers.

The increase in venous return is suggestive of an active venoconstriction, since the central volume is always greater when the interventricular shunt is open than it is in the control, regardless of total blood volume. Although this increase in central blood volume could be in part the passive consequence of the increased right ventricular pressure driving a greater blood volume into the lungs, the potentiation of this effect by a known venoconstrictor indicates that this can be an important mechanism. Evidence for reflex venoconstriction following baroreceptor hypotension has been presented by Heymans, Bouckaert, and Dautrebande[30] who demonstrated mesenteric venous constriction associated with a diminution in splenic and intestinal volumes with carotid sinus hypotension. Rashkind and co-workers[21] have shown that increased volumes of blood are displaced from the peripheral venous system when baroreceptor hypotension is simulated. The work of Sarnoff and his colleagues[35, 36, 37] strongly suggests that volume shifts of this magnitude could only come from the venous side of the

circulation, and Bartelstone[38] has demonstrated sizable increases in the volume of the great veins during carotid sinus hypotension.

The increase in pulmonary vascular resistance following the opening of the interventricular shunt cannot be accounted for on the basis of passive hemodynamic consequences of the shift in blood volume toward the pulmonary circulation, since, as pulmonary volume increases, pulmonary vascular resistance would be expected to decrease at any given flow. Indeed, the studies of Sarnoff, Berglund, and Sarnoff[36] and Sarnoff and Berglund[39] on the pulmonary edema engendered by the intracisternal injection of fibrin in dogs have already demonstrated that arteriolar and venoconstriction associated with large shifts of blood volume from the periphery is associated with an actual decrease in pulmonary vascular resistance. The case for active pulmonary vasoconstriction is strengthened by the fact that bronchial arterial pressure is either the same or lower than in the control. If we view this pattern of response as a reflex mediated by the stimulus of baroreceptor hypotension then the work of I. de Burgh Daly and M. de Burgh Daly[40] would lend strong support to this observation. These investigators found that carotid sinus hypotension caused an increase in pulmonary vascular resistance which could be reversed by baroreceptor hypertension and abolished by ablation of the cardiac sympathetic efferent nerves.

Perhaps the best evidence for the reflex adjustment of the cardiac compensation to the acutely induced ventricular shunt is the shift of the ventricular function of the right ventricle to a more efficient curve. Although the work of von Anrep[41] and Mitchell, Gilmore, Linden, and Sarnoff[42] indicates that when the ventricle is faced with a higher pressure, some degree of autoregulation may occur producing evidence of a positive inotropic effect; this poorly understood phenomenon is probably only of minor importance in the compensation to an acute ventricular septal defect, although it may be of some significance when right ventricular pressure is elevated by pulmonary artery constriction. The increased myocardial contractility, in evidence when the interventricular fistula is open, is almost certainly indicative of increased cardiac sympathetic nervous activity and/or the elaboration of catechol amines from the adrenal medulla, both of which are reflex activities. As Sarnoff and his coworkers[43] have elegantly demonstrated, the carotid sinus reflex is of major importance in regulating the efficiency of myocardial contraction and that this mechanism plays its role by shifting ventricular function from curve to curve in compensation for changes in baroreceptor hypotension. In relating the alterations in ventricular function produced by infused l-norepinephrine to those attendant on changes in carotid sinus pressure, Siegel and Gilmore[44] have shown that catechol amines are released within the myocardium by sympathetic nerves in response to baroreceptor hypotension.

SUMMARY AND CONCLUSIONS

It would appear as if the compensatory cardiovascular mechanisms which come into play in response to an acute ventricular septal defect are (1) an increased rate and cardiac output, with the output changes being more important

than the chronotropic ones, (2) an increased peripheral arteriolar resistance, (3) peripheral venoconstriction with a resultant shift in circulating blood volume toward the cardiopulmonary area, (4) increased pulmonary vascular resistance, and (5) a shift of myocardial ventricular function to a more efficient curve. The first of these mechanisms is directed toward maintenance of forward output and may be, in large part, a function of venous return to the heart. The second mechanism is directed toward the maintenance of systemic arterial blood pressure and consequently coronary perfusion pressure, and actually tends to increase the shunt at the ventricular level, with a consequent reduction in forward flow. The third and fourth mechanisms have as their end result an increase in resistance presented by the right ventricle to shunted flow and a net increase in forward output. The fifth mechanism enables the myocardial pump to handle the increased work demands placed upon it by compensation.

The experimental evidence presented indicates that this compensation can be assisted by increasing venous blood volume over a fairly wide range, thus allowing the venoconstrictor effects, with their resultant increase in central volume, to become more prominent. The increase in central blood volume and its related beneficial effects on forward output can be potentiated by the use of a sympathomimetic vasoconstrictor agent; but the venomotor action of such an agent must be weighed against its arteriolar constrictor effects, and the latter appear to be relatively more important at low blood volumes.

An extra dividend from the proper use of a sympathomimetic, such as l-norepinephrine, is the resultant increase in pulmonary vascular resistance, and, more important, the improvement of the efficiency of myocardial contractility.

It is suggested that all of the mechanisms of compensation to an acute interventricular shunt, except for the initial increased venous return produced by the shunt, can be brought into play by the observed unbalancing of the equilibrium of a single group of afferent receptors—the baroreceptors of the aortic arch and carotid sinus. Viewed in this way, the otherwise unrelated events occurring in the cardiovascular system in response to this stress become understandable as components of a well-established reflex pattern of adaptation.

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STRIP GRAFTING IN CORONARY ARTERIES

Report of a Case

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THE INCIDENCE of coronary sclerosis seems to be increasing, and in Sweden the annual mortality rate from myocardial infarction is at present 3:10,000 in men belonging to the age group of 30-50 years. Since medical treatment is of limited value, a surgical method for direct intervention on the coronary arteries has been devised. As yet, no clinical attempts to make anastomoses between systemic and coronary arteries or grafts in coronary arteries seem to have been reported. Other means have been sought, and May has elaborated a method for coronary endarterectomy, applied clinically by Bailey.[1] Cannon and Longmire,[2, 3] using another technique, have performed endarterectomy on 10 patients, with 5 survivals.

If a direct surgical intervention on the coronary arteries is to be successful, the following prerequisites must be fulfilled. The clinical features must be caused by a process relatively well confined to the large coronary vessels, and the vessels distal to them must be patent. It must be possible to localize exactly the extent of the occlusive changes preoperatively, by means of angiography. Removal of the impediment must take place without injury to the small vessel branches given off from the operative region, or distal to it in the affected vessel.

At the Department of Experimental Surgery, we have been working on the problem in question for about 2 years. Since we found that conventional thoracic aortography did not always give satisfactory, equal opacification of both coronary arteries, a stereoscopic method for coronary angiography, which allows exact localization of occlusions of these arteries, was elaborated.[5] At the same time, a technique was devised for strip grafting in the coronary arteries, and has been used experimentally in the dog with good results.[6, 7] This operation is performed under extracorporeal circulation with a double pump, combined with hypothermia (20° to 23° C.), a strip cut lengthwise from the internal mammary artery being sutured into the split coronary artery.

At present, coronary angiography is used for examination of patients with definite angina pectoris, if they are under 60 years of age. In those found to have marked, diffuse coronary lesions, a modified Beck operation is done. In patients with relatively well-localized changes, we intend to perform coronary transplantation with an autologous strip graft from the great saphenous vein, taken at the malleolus. Such patients have well-developed intercoronary anastomoses, which—after removal of the occlusion in a large artery—allow an

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improved blood flow to the whole myocardium, even if occlusions are still present in other branches. Moreover, the coronary anastomoses provide adequate peripheral drainage from the branch in which the graft is inserted, so that there is a good chance of the graft remaining patent. A report follows of the first case in which coronary strip grafting was performed.

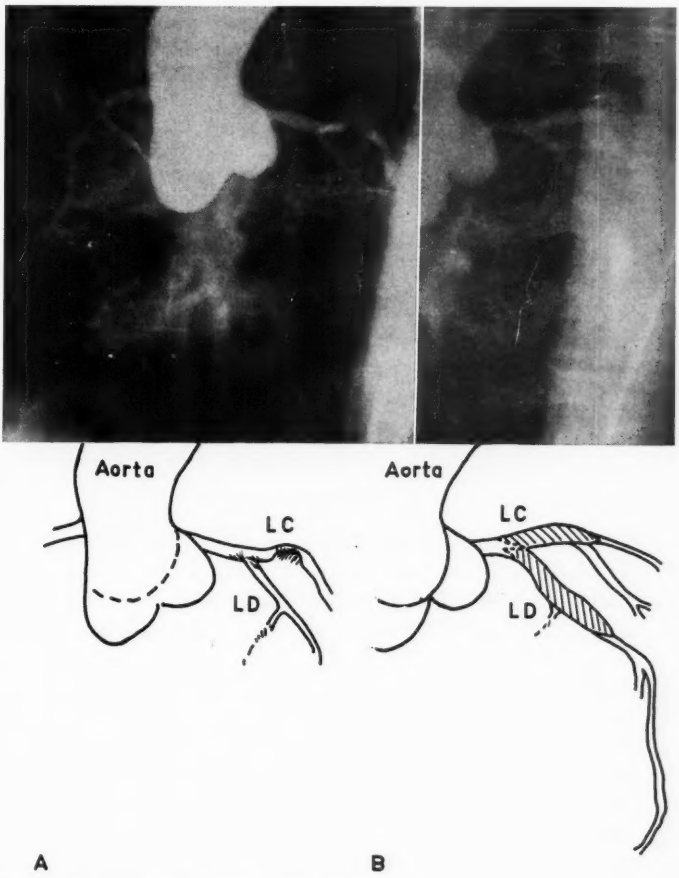

Fig. 1.—*A*, Preoperative coronary angiography.
B, Postoperative coronary angiography (3 months after operation).
LC—Left circumflex coronary branch. *LD*—Left descending coronary branch. The hatched areas on schematic drawing *B* represent the grafts.

CASE REPORT

The patient, a 55-year-old doorkeeper, had become increasingly disabled by attacks of precordial pain since 1955, brought on by the slightest physical exertion, emotion, large meals, or cold. In 1956 he was hospitalized for signs of a myocardial infarction. In 1958 he was readmitted to the hospital because of severe precordial pain; no definite infarction occurred. He had intermittent periods of arrhythmia of the extrasystole type. He had been treated with nitroglycerin, and recently with heparin administered subcutaneously.

His general condition was fairly good; pyknic, corpulent (weight 88 Kg., height 164 cm.) with no signs of heart failure; the heart rhythm was regular, sounds pure; blood pressure was 130/80 mm. Hg; the electrocardiogram (see Fig. 3, *1*) showed slight left axis deviation, intraventricular conduction defect in the left ventricle; there were signs of severe, generalized coronary and myocardial insufficiency, most marked in the left ventricle; phonocardiography revealed no murmurs; roentgenologic examination showed the heart slightly enlarged, total volume 1,040 ml. representing 520 ml./M.^{2} of body surface. The heart was of ordinary shape; no calcifications.

Physical working capacity (bicycle ergometer test) with electrocardiogram during exercise could not be evaluated, since the patient had anginal pain on attempts without load.

Coronary angiography (Nordenström—Fig. 1, *A*): Two centimeters from its origin, the right coronary artery branched into a number of small vessels. One of them had an irregular lumen, as in atheromatosis. An abundant vascular network was given off from the right coronary artery. The left coronary artery was slightly narrowed at its origin from the aorta. An additional narrowing was present at the site of origin of the anterior descending and circumflex branches. The first 2 cm. of the descending branch were opacified, whereas the rest of its interventricular part was not filled; at this site, tortuous collateral vessels were visible. Its first left descending branch was opacified slowly. It was greatly narrowed at the origin, and its lumen was highly irregular. In the circumflex branch, about 1.5 cm. from its origin, there was severe stenosis of a portion about 1 cm. long, after which the vessel regained the same width as above the stenosis. The distal part of the artery was narrowed.

In view of the patient's severe pain and disablement, operation was considered to be indicated. Since the occlusive changes in the circumflex and descending branches of the left coronary artery were relatively well localized, it seemed likely that strip grafting would improve the blood flow to the myocardium.

OPERATION

Coronary strip grafting in the circumflex and descending branches of the left coronary artery.

Anesthesia (Norlander).—Pentothal, Fluothane, and Celocurin. Extracorporeal circulation with the AGA automatic double pump, combined with hypothermia, induced with a heat exchanger.

Bypass was first performed with one half of the double pump from the left atrium to the femoral artery, via the heat exchanger, for cooling. Initially, the flow was 1 L. per minute, the inflowing blood being cooled to 14° C. The flow was then increased to 2.8 to 3.0 L. per minute, with the inflowing blood cooled to 15° C. The coronary arteries were dissected out during this period of slow cooling. When dissection was completed, the "right" pump (from right atrium to pulmonary artery) was also connected, after which circulation in the left coronary artery was interrupted. The cooling period lasted for a total of 47 minutes, the temperature being lowered to 20° C. in the esophagus and 26.6° C. in the rectum, in which it fell gradually to 23.7° C.

When suturing of the grafts into the coronary arteries was almost completed, warming was started. In the course of 35 minutes, with a flow of 1.6 to 3.0 L. per minute and the inflowing blood warmed to 26° to 33° C., the temperature in the esophagus rose to 31.5° C. and that in the rectum to 24.2° C. The pump for bypass of the right side of the heart was then disconnected. During bypass of the left side only, warming was continued for 30 minutes, after which

the temperature was 34° C. in the esophagus and 28° C. in the rectum. Warming was then discontinued. Throughout the period of hypothermia, the mean arterial pressure was kept at about 70 mm. Hg.

Surgical Procedure.—Transsternal thoracotomy was performed in the fourth intercostal space on the left side, from the posterior axillary line, and continued on the left side, in the third intercostal space, to the mammillary line. The pericardium was opened widely. Palpation of the coronary vessels disclosed changes in the right side corresponding to the angiographic findings. In the left coronary artery, there was severe sclerosis and calcification, both of the main trunk and of the circumflex branch, as well as of a 3.5 cm. portion of its first descending branch. The main trunk and the first 5 cm. of the circumflex branch, as well as of the first descending branch, were dissected out, and sling ligatures applied to all the large branches.

When dissection was completed, total bypass was started, and circulation was interrupted both in the main branch of the left coronary artery and in the large branches. The descending branch was incised, and split lengthwise from its site of origin to 4 cm. distal to this point (Fig. 2, *A*). The vessel was greatly sclerosed, with calcifications, and in one place seemed to be completely occluded. Partial endarterectomy was done in this region. A 4 cm. length of the great saphenous vein, taken at the malleolus, was split lengthwise and the ends cut into points, after removal of periadventitial tissue. The graft was sewn in lengthwise with continuous over-and-over sutures (Fig. 2, *B*). In a few places in which the coronary artery wall was in poor condition, some extra stay sutures had to be made afterwards.

The circumflex branch was then split longitudinally for a length of 3 cm. from the bifurcation. Since the actual site of branching of the vessel was also narrowed, the incision was continued for 0.5 cm. proximal to it. Another 3.5 cm. long strip graft was sutured into the incised artery. When this was finished, the ligatures round the main branch and the small branches were released. Since fairly brisk hemorrhage ensued, it was necessary—for the vessels to be completely devoid of blood—to occlude the aorta intermittently during definite arrest of the bleeding by means of extra sutures.

Warming of the patient was started while continuing to check the bleeding. The circulation in the left coronary artery had then been completely cut off for more than 2 hours at a stretch, and was subsequently occluded intermittently while the hemorrhage was arrested. Although ventricular fibrillation had been present for more than 2 hours, the heart was never completely flaccid. During occlusion of the left main trunk of the coronary artery, some blood flow to the left ventricle took place continuously, through intercoronary anastomoses.

When the temperature in the esophagus had risen to 28° C. the first attempt at defibrillation was made with electroshock (2.5 amp. for 0.16 sec.), and the heart then resumed its normal rhythm for about 1 minute. Warming was continued, and 6 to 7 minutes later a new attempt was made to defibrillate by electroshock. This resulted in rhythmic contractions of the heart for 10 minutes,

after which ventricular fibrillation once more appeared. After a third defibrillation, the heart continued to contract rhythmically, and the aorta pulsated strongly.

When the temperature was 31.5° C. in the esophagus and 24.2° C. in the rectum, the pump for bypass of the right side was disconnected. The heart then contracted rhythmically and strongly, interrupted by occasional extrasystoles. The pump for bypass of the left side was allowed to run for an additional 30 minutes, to continue warming and to decrease the load on the left side of the heart. Toward the end of this period it was stopped gradually. The temperature had then risen to 34° C. in the esophagus and 28° C. in the rectum,

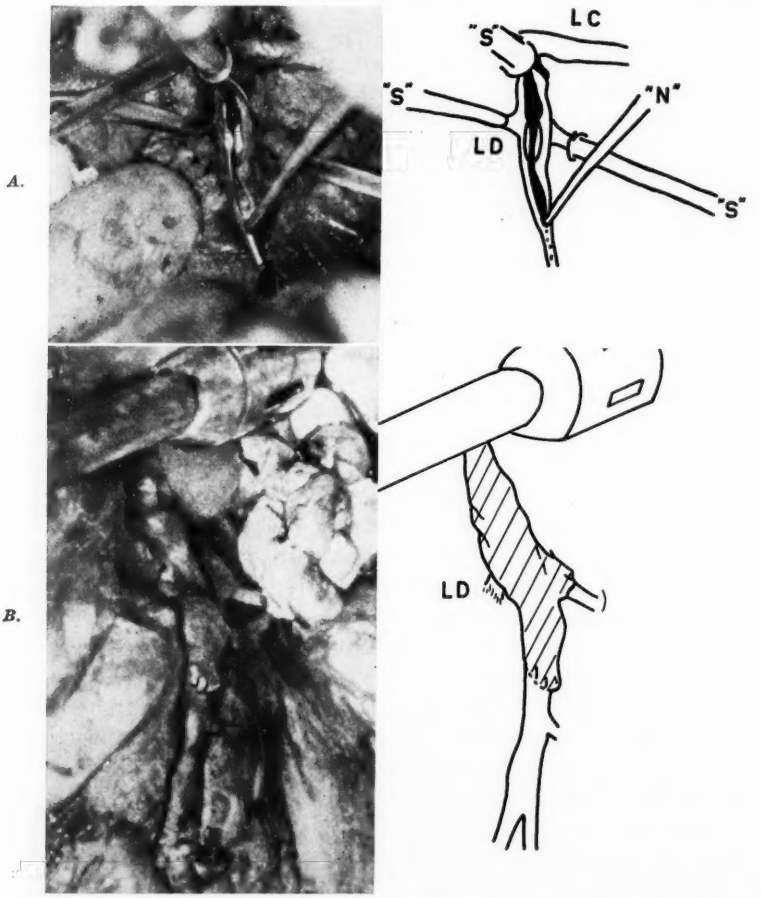

Fig. 2.—*A*, During incision of left descending coronary branch. The vessel is narrowed by extensive calcifications. Probe (*"N"*) in lumen serves as a guide.

B, Graft sutured into the descending branch of the coronary artery.

LC—Left circumflex coronary branch. *LD*—Left descending coronary branch. *"S"*—Tubes for sling ligatures.

and the patient's blood pressure was good. Meticulous hemostasis was done. A tube was inserted in each pleural cavity. The pericardium was sutured over the grafted region, but was otherwise kept open. The chest wall was sutured in layers.

The patient woke rapidly after operation. The electroencephalogram had been normal throughout. Since he was extremely fat, tracheotomy was performed in view of the transsternal thoracotomy, and he was placed in a respirator for 3 days. Full doses of digitalis were given.

Since the hemoglobin level fell from 14.4 Gm. per cent preoperatively and 14.8 Gm. per cent postoperatively to 8.4 Gm. per cent 3 weeks after operation, blood transfusions were given. In other respects, the postoperative course was completely uneventful.

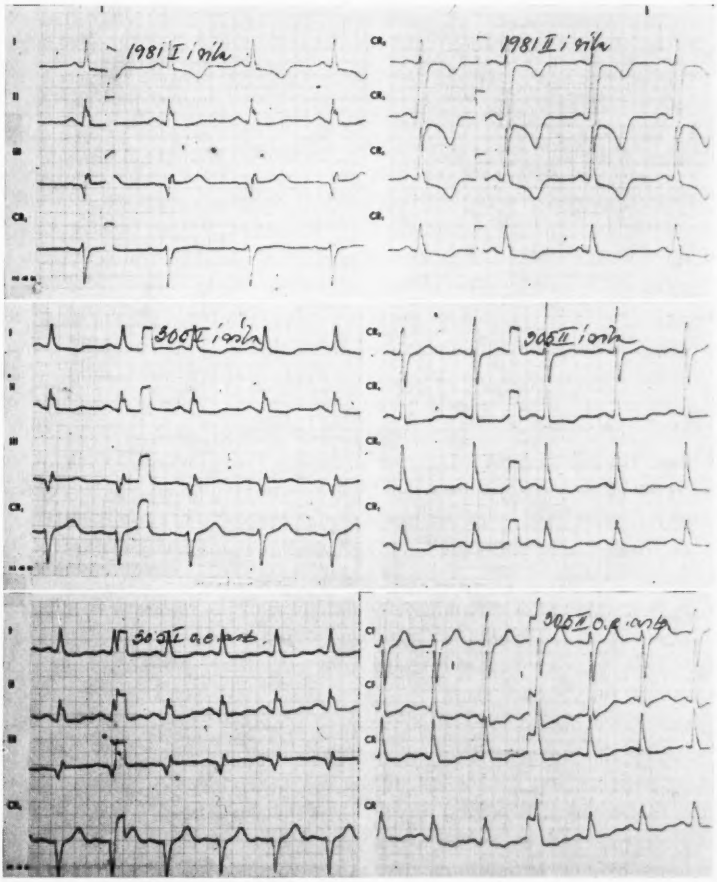

Fig. 3.—*1*, Electrocardiogram at rest preoperatively. *2*, Electrocardiogram at rest 3 months after operation. *3*, Electrocardiogram immediately after exercise (400 Kg./min.—6 min.) 3 months after operation.

Results.—Three months after operation, the patient was hospitalized for a follow-up examination. He had complete freedom from anginal pain and was able to work without difficulty. The electrocardiogram (Fig. 3, *2*) showed less marked depression of S-T segments than preoperatively. There were signs of coronary insufficiency and myocardial involvement, corresponding to the left ventricle.

Physical working capacity (bicycle ergometer test): With a load of 200 Kg. per minute for 6 minutes, the pulse rate was 140 per minute, and with a load of 400 Kg. per minute for 6 minutes it was 154 per minute. The patient had no anginal pain, but his legs became tired. During and after exercise, no definite changes were observed on the electrocardiogram (Fig. 3, *3*).

Angiography (Fig. 1, *B*): Two grafts in the shape of a V were present in the left coronary artery, at the site of the first bifurcation. One graft was inserted in the circumflex branch, and the other in the descending branch of the left coronary artery, continuing into its first descending branch. There was good patency of both grafts.

COMMENTS

The case reported shows that it is possible to make a transplantation in the coronary arteries. The advantage of the grafting technique described is that it widens the coronary vessel, but causes no damage to the site of origin of the vessels given off from the affected region or distal to it.

Technically, it is possible to perform endarterectomy of the main arteries and even of the large branches given off from them. Experimentally and clinically, the method has not, however, been successful in our hands. Histologic examination showed that the intima had been torn off at the origin of the smaller vessels given off from the endarterectomized region, and that most of these vessels were thrombosed. Postoperative coronary angiography, after "successful" endarterectomy of a short, localized partial occlusion (performed at another hospital) disclosed total occlusion of the coronary branch involved.

In the presence of well-localized occlusion of coronary arteries, good circulation can be restored. If, as in our patient, the changes have a more diffuse extent, it is nevertheless possible—if good patency is restored in one or more large branches—to anticipate an improved blood supply to the myocardium as a whole. This is because intercoronary anastomoses are present in patients with long-standing, partial occlusion.

In the case reported here, postoperative coronary angiography showed complete patency of the grafts. The electrocardiogram seemed to be improved, despite some persisting depression of the S-T segments. No additional electrocardiographic changes appeared during the functional test. Thus, the patient is both subjectively and objectively improved.

Consequently, it is our hope that the method described can be used in the future for operation of patients with angina pectoris, who have well-localized occlusion of the coronary arteries, either of arteriosclerotic or other origin.

SUMMARY

A report is given of a 55-year-old man, disabled by angina pectoris, with angiographically localized occlusion of the coronary arteries. Operation was performed, with insertion of strip grafts in the circumflex and descending branches of the left coronary artery. Three months after operation, coronary angiography shows patency of both grafts and the electrocardiogram shows improvement. The physical working capacity of the patient is improved and, 5 months after operation, he is still asymptomatic.

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A CASE OF ANOMALOUS DRAINAGE OF THE SUPERIOR VENA CAVA INTO THE LEFT ATRIUM

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THE CLINICAL significance of anomalies of the superior vena cava has assumed increasing importance in the ever-widening scope of corrective cardiac surgery. As with anomalies of veins elsewhere in the body, great variation may be encountered in superior vena caval anatomy.[1, 2] In general, however, two categories may be described: (1) anomalies of position, and (2) anomalies of drainage. Anomalies of position, such as a persistent left superior vena cava, occur more frequently than those of drainage and are not inherently productive of a physiologic abnormality.[2, 3] Venous blood is drained from the left superior vena cava into the right atrium via the oblique vein of Marshall and coronary sinus; thus, no right-to-left shunt is afforded. Anomalous drainage of the superior vena cava into the left atrium is, however, a very rare anomaly. This defect produces a large right-to-left shunt, and in all previously described cases has been associated with a persistent left superior vena cava.[1, 4-7] In only 1 of the 24 cases previously described in the world literature of abnormal drainage of the superior vena cava has there been no other major cardiac anomaly.[6] The case that we report is unique because it represents the first example of a normally situated right superior vena cava draining into the left atrium as an isolated anomaly. This case is also the first example of correction of anomalous superior vena caval drainage by transposition of the vessel to the right atrium.

CASE REPORT

Patient L. B., a 2-year-old white girl, was born after a normal pregnancy. She became cyanotic at the age of 1 month, but her growth and development continued normally. At the age of 11 months she was first seen at St. Louis Children's Hospital because of the development of cyanosis. The arterial oxygen saturation was 76 per cent. No abnormalities of the heart or lungs could be detected on physical examination. There was no blood chemical evidence of sulfmethemoglobin or methemoglobin. An electrocardiogram was within normal limits, but chest x-ray studies indicated hypoplasia of the right ventricle as in tricuspid atresia (Fig. 1). The patient was re-examined at the age of 18 months at which time she had developed definite clubbing of the fingers. She was then admitted to St. Louis Children's Hospital for the first time and cardiac catheterization was performed via the right saphenous

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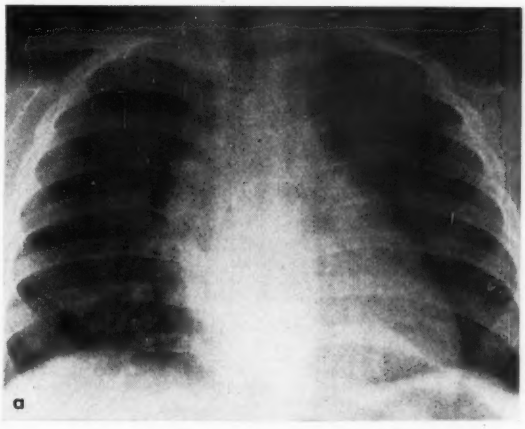
vein. The studies indicated normal pressures in the right chambers of the heart and pulmonary artery, and no left-to-right shunt was demonstrated. An angiocardiogram with the catheter in the right ventricle indicated an intact interventricular septum and normal pulmonary artery. The right upper pulmonary vein was seen to enter the left atrium in a more caudad position than normal. The contrast medium in the aorta was more dilute than normally, but no dilution effect was seen in the left atrium (Fig. 2). Angiocardiography was



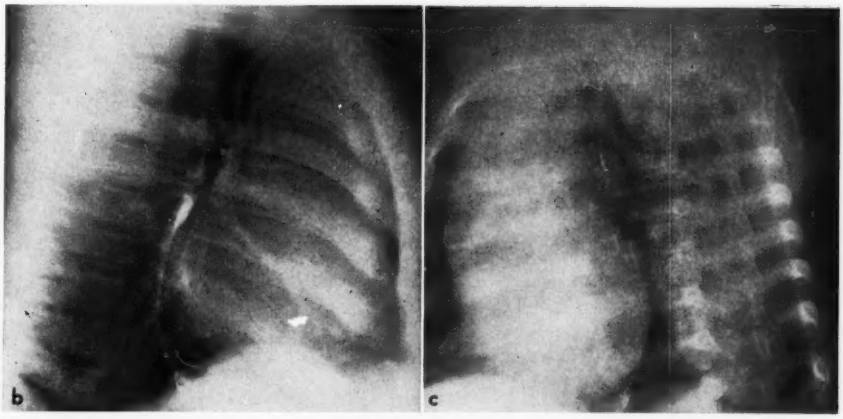


Fig. 1.—Plain films of the chest in anteroposterior, left lateral, and left anterior oblique projections. Moderate enlargement of the left ventricle is noted in all projections. The pulmonary vessels are normal. In the left anterior oblique projection the right cardiac contour is less prominent than normally, which indicates less than normal size of either the right ventricle or the atrium.

then performed utilizing a left antecubital vein, and this demonstrated transposition of the right superior vena caval drainage into the left atrium (Fig. 3). After this anomalous right superior vena caval drainage had been established, the child was evaluated by the chest surgical service.

At the age of 22 months the child was operated on by Dr. Thomas Burford for surgical correction of the anomaly. Utilizing a right posterolateral thoracotomy incision with normothermic anesthesia, easy access was gained to the superior vena cava and atrium. The

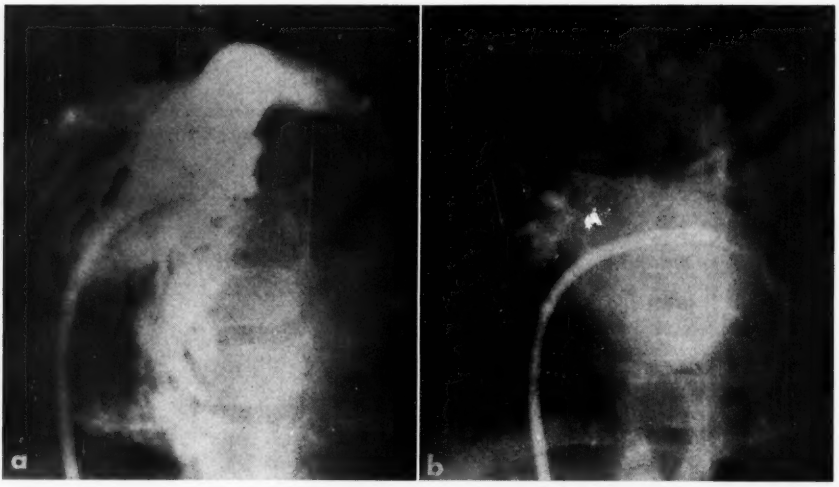


Fig. 2.—Angiocardiography with injection of the contrast medium into the right ventricle. The patient is slightly rotated to the right in the anteroposterior projection. The illustration to the right shows the contrast medium in the left atrium after passage through the pulmonary circulation. No dilution effect is seen. The pulmonary veins enter the left atrium in a normal way except that the upper right pulmonary vein enters more caudad than normally, displaced by the superior vena cava.

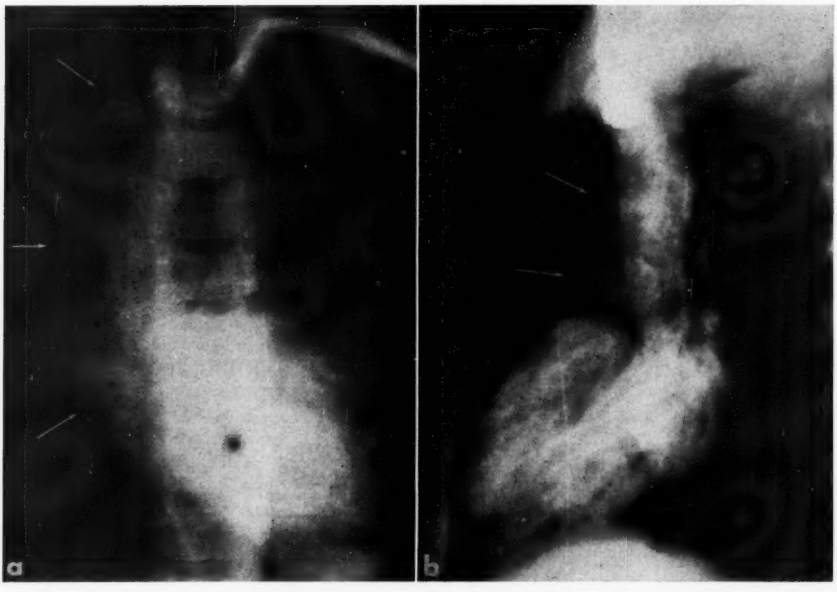


Fig. 3.—Intravenous angiocardiography from the left antecubital vein. The contrast medium is seen to enter the normally placed right-sided superior vena cava via the left subclavian and innominate vein. However, the superior vena cava opens into the left atrium and contrast medium passes via the left ventricle out into the aorta. No anomalous connection between the right and left chambers of the heart or the pulmonary artery is present.

superior vena cava was noted in its usual right mediastinal position. After incising the pericardium the right superior vena cava was seen to course into the superior pole of the left atrium. The right atrium appeared small. To facilitate the anastomosis between the superior vena cava and right atrium, the azygos vein and two small anastomoses between the right pulmonary vein and right superior vena cava were ligated and divided. The superior vena cava was clamped, divided just above its entrance into the left atrium, and then anastomosed to the right atrium. The superior vena cava was clamped for 35 minutes during the anastomosis to the right atrium. The child's postoperative course was marked by the dramatic disappearance of cyanosis. Recovery was prompt and the arterial oxygen saturation was 96 per cent on the eighth postoperative day. The child was discharged in excellent condition 10 days after operation.

COMMENTS

From an embryological as well as clinical standpoint, this anomaly of a right superior vena cava draining into the left atrium is unprecedented. In order to hypothesize the sequence of developmental faults capable of producing a defect such as this, it is necessary to review briefly the embryology of the establishment of systemic venous return to the right atrium. In the embryonic

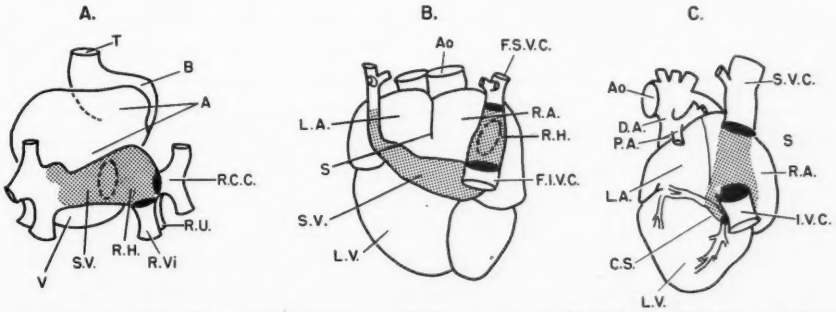


Fig. 4.—Schematic dorsal view of developing heart to illustrate absorption of sinus venosus *(stippled area)* and changing relationship of orifices of future superior vena cava, inferior vena cava, coronary sinus *(black area)*, and aperture of sinus venosus *(broken line ellipse)*. *A*, 22 somites. *B*, 7 mm. embryo. *C*, Newborn. A rightward deviation of the intra-atrial septum would appear to place the inferior vena cava in left atrium (after Arey).

CODE: *T*, truncus; *B*, Bulbis; *A*, common atrium; *R.C.C.*, right common cardinal vein; *R.U.*, right umbilical vein; *R.Vi.*, right vitelline vein; *R.H.*, right horn of sinus venosus; *S.V.*, sinus venosus; *Ao*, aorta; *F.S.V.C.*, future superior vena cava; *R.A.*, right atrium; *F.I.V.C.*, future inferior vena cava; *L.V.*, left ventricle; *D.A.*, ductus arteriosus; *P.A.*, pulmonary artery; *C.S.*, coronary sinus; *S.V.C.*, superior vena cava; *I.V.C.*, inferior vena cava; *S*, intra-atrial septum; *L.A.*, left atrium.

tubular heart, systemic venous return to the common atrial chamber is accomplished via an antechamber, the sinus venosus.[8] This reservoir is originally a midline, bicornuate structure into which drain the vitelline, umbilical, and cardinal venous systems (Fig. 4, *A*). From the sinus venosus blood then enters the atrial chamber through an elliptical aperture. The long axis of this aperture at first parallels the long axis of the heart, but, with the advent of the atrial septum primum, it assumes a right-sided position. The cephalic pole of the aperture eventually is situated farther to the right than the caudal pole. As the right common cardinal and vitelline veins, forerunners of the superior and inferior vena cava, assume greater functional importance, so the right horn of

the sinus venosus becomes enlarged relative to the left. In the ten to twenty millimeter embryo, the enlarged right horn of the sinus venosus, as well as a portion of the transverse horn, becomes incorporated into the right atrial wall and loses its configuration as a chamber.[9] Thus, the apertures of the future inferior and superior vena cava, as well as the coronary sinus, then open directly into the right atrium instead of the sinus venosus. As right atrial enlargement continues, there is a relative cephalad movement of the aperture of the future superior vena cava, whereas the apertures of the future coronary sinus and inferior vena cava remain approximated in a caudal position (Fig. 4, *B* and *C*).

Thus, in order to account for the aperture of the superior vena cava in the left atrium as an isolated anomaly, it seems likely that an abnormality of the right horn of the sinus venosus is the etiological factor. An anomaly of atrial septal development is the other possibility for this disorder, but seems unlikely on the basis of the developmental anatomy of the various apertures in the right atrium. If a rightward deviated atrial septum is postulated as the etiology, it is difficult to conceive how the apertures of the future inferior vena

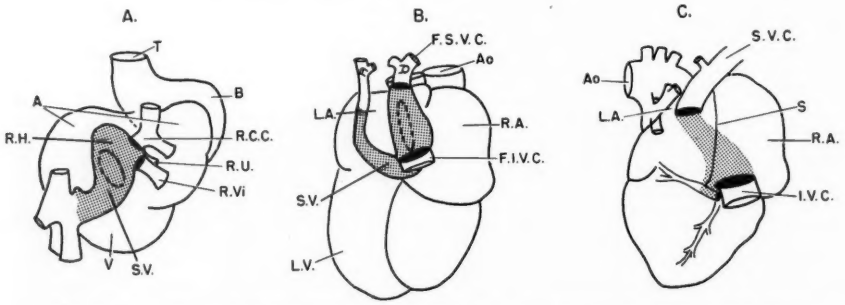


Fig. 5.—Hypothetical malformation of primitive sinus venosus to account for superior vena caval drainage into left atrium. Same stages and code as Fig. 2. Note the relative leftward shift of the right horn of sinus venosus.

cava and coronary sinus could remain in the right atrium. These apertures are normally situated closer to the left atrium than that of the superior vena cava, and any atrial septal malposition to the right would appear to encompass the former in the left atrium more readily than the latter (Fig. 4, *B* and *C*).

The hypothetical explanation that best seems to explain this remarkable anomaly consists of a malposition of the right horn of the sinus venosus (Fig. 5, *A*). If the right horn of the sinus venosus developed aberrantly with relative leftward and cephalic distortion, the aperture of the superior vena cava alone could be placed in the left atrium. This could occur in association with a normally developed interatrial septum. Fig. 5 (*A*, *B*, and *C*) indicates schematically how such development could take place. However, the anomaly that we have recorded is not completely documented, in that we are not sure of where the coronary sinus drains in this case. We have assumed that there are no other major cardiac defects present on the basis of inferential evidence

from the cardiac catheterization and angiocardiogram. We have merely constructed a hypothesis drawing attention to the possibilities of derangements of the primitive sinus venosus in the etiology of this particular congenital cardiac disorder. The clinical considerations in this case were extremely puzzling until superior caval angiography was performed. The patient presented the problem in the diagnosis of a cyanotic, otherwise normally developed, infant. No readily apparent cardiac, pulmonary, or metabolic cause for the cyanosis could be postulated. On the basis of a small right ventricle in early studies, tricuspid stenosis was suspected but ruled out after normal right heart catheterization data. The clinicians caring for this child considered an anomaly of superior vena caval drainage, with a right-to-left-shunt, prior to the performance of left heart angiocardiography. This assumption was largely postulated by exclusion. The angiocardiograms demonstrated unequivocally the suspected transposition of the right superior vena cava.

The physiologic stress of this rather massive right-to-left shunt, approximately 30 per cent of the systemic venous return,[10] was well tolerated in this infant. In the one previously reported case of an isolated anomaly of drainage of the left superior vena cava into the left atrium, the patient was practically asymptomatic until early adolescence.[6] At this time left ventricular hypertrophy supervened without frank cardiac decompensation. It is of interest as well that, with a previously reported instance of an inferior vena cava draining into the left atrium, there was minimal evidence of cardiac and general physical disturbance.[11] It is not apparent why defects of this magnitude should be so relatively well tolerated.

There have been three previously reported attempts at surgical correction of abnormal drainage of the superior vena cava into the left atrium.[6, 12, 13] Two of these cases consisted of a persistent left superior vena cava draining into the left atrium, associated with a right superior vena cava draining into the right atrium. Other cardiac defects were present in both cases, and abnormal superior cava drainage was eliminated by ligation and division of the left superior vena cava. The other previously reported attempt at surgical repair was an isolated left superior vena cava draining into the left atrium.[6] The procedure was unsuccessful and the patient died in the immediate postoperative period. The case that we have presented represents the first successful correction of an isolated superior vena cava drainage anomaly by transposition of the vessel to the right atrium.

SUMMARY

The first documented instance of a right superior vena cava draining into the left atrium as an isolated cardiac anomaly is presented. A hypothetical explanation is provided for the development of this anomaly on the basis of malposition of the right horn of the sinus venosus. The defect was surgically corrected by division of the superior vena cava with anastomosis to the right atrium.

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A NEW APPARATUS FOR THE WIRING OF ANEURYSMS

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IN THE TREATMENT of aneurysm of the thoracic or abdominal aorta, replacement of the diseased segment by a graft is the treatment of choice. However, various circumstances may militate against selection of such a procedure. In these cases introduction of wire into the aneurysmal sac may offer the patient a long period of symptomatic relief.

The most common practice is to pass the wire through a lumbar puncture needle, the tip of which has been inserted through the wall of the aneurysm into its lumen. The wire is grasped between the thumb and index finger, or by forceps, and is fed through the needle at the rate of about one-half inch with each thrust. Attempts to pass the wire faster by feeding greater increments into the needle invariably result in kinking of the wire. Kinking is also produced as the wire encounters greater resistance in the needle because of the presence of clotted blood. In either case, the wire must be withdrawn and cut at the kink, the free end of the wire sticking through the wall of the aneurysm must be safely tucked inside the lumen, the needle rethreaded and wiring resumed. In order to insert several hundred feet of wire into an aneurysm the surgeon is faced with a long, fatiguing and, often, frustrating procedure. In addition, there is usually considerable loss of blood through the needle, necessitating constant blood replacement during operation.

A description follows of the apparatus we have designed to overcome the objectionable difficulties usually encountered.

DESCRIPTION OF APPARATUS

The device (Figs. 1 and 2) consists of a small stainless steel box (*A*) having one transparent Plexiglas side (*B*). Within the box are two wheels having a diameter of $1\frac{1}{16}$ inch and a thickness of $\frac{1}{8}$ inch. One of these is a driving wheel (*C*) and the other is an idling wheel (*D*). The rim of the idling wheel is flat. The rim of the driving wheel is grooved to receive the idler. The bearing holes for the shaft of the idling wheel (*E*) are elongated, allowing for lateral displacement of the wheel. However, the idling wheel is kept in firm contact with the driving wheel by means of a forked phosphor-bronze leaf-spring (*F*) which exerts constant pressure on the shaft. This permits wire of different thicknesses to be gripped securely between the driving wheel and

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the idler. The shaft of the driving wheel projects through the transparent side of the box and supports a wheel ¾ inch in diameter on which is mounted a small crank (*G*). The top of the box has a small funneled aperture (*H*) to receive the wire from the spool and position it precisely between the driving wheel and idler. The bottom of the box has another funnel (*J*) which receives the wire as it emerges from between the wheels and guides it into the needle. Thus, by turning a crank in a clockwise direction, the wire is drawn into the box from the spool, the latter being held on a mandrel at a convenient height above the operating field by an assistant. The wire is fed into the needle. Because of the short distance between the driving wheel and the needle the tendency to kink is largely abolished. Also, because the idling wheel is held against the driving wheel by means of a spring, slipping, rather than kinking, occurs if the resistance in the aneurysm increases. This provision for slipping also guards against penetration of the wall of the aneurysm by a wire which is too stiff to curl as it leaves the needle. Each turn of the crank on the driving wheel introduces 2 inches of wire into the aneurysm. If the wheel is turned at the rate of one revolution per second, one would theoretically introduce 10 feet of wire per minute. One can easily turn the driving wheel two revolutions per second. In a recent case the surgeon introduced 300 feet of wire in approximately 15 minutes.

Should kinking occur, it will take place just distal to the driving wheels. Because the face of the box is transparent one can readily differentiate between slipping and kinking. If the wire should kink it is pulled out beyond the point of kink and cut about 1 in. above the surface of the box. A No. 21 gauge hollow needle (*K*) with its stylet (*L*) withdrawn about 1 in. is then threaded over the protruding cut end. The needle is passed through the box between the wheels and into the needle inserted into the aneurysm. The combination needle and stylet are about 1 or 2 mm. longer than the wiring needle in the aneurysm. Thus, when the needle is fully introduced and the stylet inserted its full length, the cut end of the wire has been pushed into the aneurysm. This maneuver requires very little time and is extremely effective in accomplishing its purpose. The fact that the idling wheel is held against the driving wheel by a spring which allows lateral displacement makes it possible to introduce wire or needles of varying gauge since the idling wheel moves to accomodate each size.

The hub of the wiring needle is firmly mounted on a small steel plate (*M*) which is fastened to the bottom of the box by two set-screws (*N*). Between the plate and the bottom of the box is inserted a small strip of surgical rubber dam (*O*). Holes in the rubber dam to allow free passage of the set-screws are punched in exact position by means of a punch-die (*P*) made for the purpose. A fresh dam is used for every operation. This is stretched over the punch-die and the holes are made by striking the punch (*Q*) with the combination hammer and screwdriver (*R*). As the wire passes between the wheels into the hub of the wiring needle, it pierces the rubber dam with a slight clicking sound. The rubber hugs the wire closely and prevents leakage of blood from the wiring needle.

Set into the hub of the wiring needle is a small nipple (*S*) to which is fastened a rubber catheter attached to a small syringe which contains heparin and saline solution. This permits frequent flushing of the lumen of the wiring needle and reduces to a minimum the tendency for blood to clot in the needle. Free, unhampered progress of the wire through the needle is thus assured.

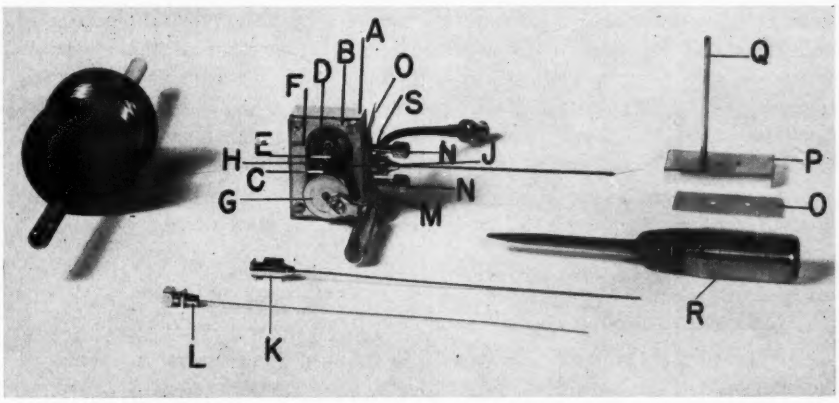

Fig. 1.—Apparatus for wiring of an aneurysm. *A*, Stainless steel box; *B*, Plexiglass face; *C*, driving wheel; *D*, idling wheel; *E*, elongated hole for bearing of idler; *F*, phosphor-bronze spring which exerts constant pressure on shaft of idler; *G*, crank-wheel and handle; *H*, receiving funnel; *J*, funnel to deliver wire into aneurysm needle; *K*, No. 21 gauge hollow needle to fit over cut end of wire protruding from aneurysm needle; *L*, stylet to fit needle *K* and push cut end of wire safely into lumen of aneurysm; *M*, plate which fastens wiring needle to box; *N*, set-screws for fastening plate *M* to box; *O*, surgical rubber dam; *P*, punch-die for making holes in rubber dam; *Q*, punch; *R*, hammer and screwdriver; *S*, nipple attached to hub of aneurysm needle to which is connected a rubber catheter leading to a small syringe containing heparin-saline solution.

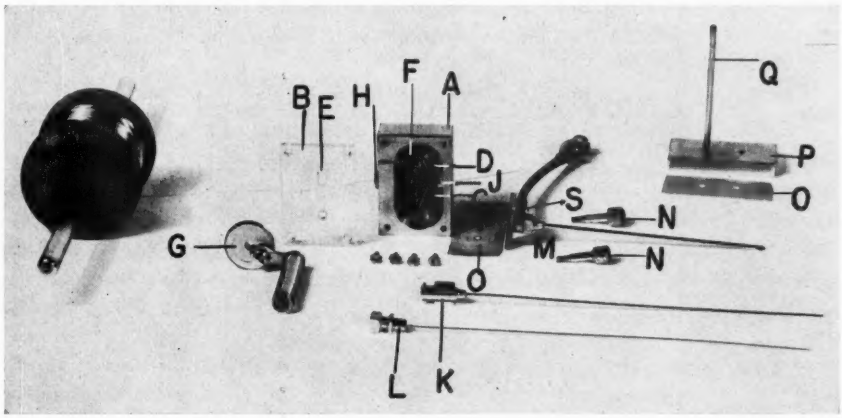

Fig. 2.—Exploded view. Legends are the same as in Fig. 1.

TECHNIQUE FOR USE OF APPARATUS

To wire an aneurysm, the site for the introduction of the needle is selected. This may require exposure by thoracotomy or laparotomy, or the needle may

be introduced transcutaneously under local anesthesia. The wire is fed into the receiving funnel at the top of the box, above which the spool is held on a mandrel at an appropriate distance and angle. The wire passes between the driving and idling wheels. Thereafter, turning the crank feeds the wire through the rubber dam into the No. 16 gauge aneurysm needle. The needle can be pointed in various directions within the aneurysm to distribute the wire uniformly; or, after wiring a portion, the needle may be withdrawn, redirected, and reinserted in order to place wire in another portion of the aneurysm. When the aneurysm is well packed with wire, increased resistance will cause the wire to slip. At this point the wire is cut about 1 in. above the box. The combination No. 21 gauge needle and stylet are employed as previously described to place the cut end of the wire in the aneurysmal sac.

At the Massachusetts Memorial Hospitals where this instrument has been in use,* surgeons prefer No. 32 gauge, 18-8 stainless steel wire.

SUMMARY

The instrument offers the following advantages:

1. There is no kinking of wire as it is stripped from the spool. When the aneurysmal sac has been filled to the degree that it offers sufficient resistance to the introduction of more wire, the latter will tend to form a loop in the box which is readily seen by the surgeon. This is an indication that the direction of the needle should be changed or that the sac has been filled practically to capacity.

2. There is complete hemostasis.

3. Hindrance to free passage of wire through the needle due to clotting induced by the "whipping" action of the wire on the blood in the lumen of the needle is entirely eliminated by occasional flushing of the lumen with heparin-saline solution.

4. Wiring is accomplished with great speed.

5. The simple cranking motion reduces hand-cramp and fatigue for the surgeon.

6. Since any power applied to the crank causes the wire to advance, the mechanical efficiency of this instrument is far superior to that of other devices which require a to-and-fro or oscillating movement, since, in the latter, the return movement of the hand after propelling the wire is wasted.

*A number of surgeons have used the apparatus, in all about 30 times. The average time for wiring aortic aneurysms varied from 15 to 30 minutes, depending upon the amount of wire inserted.